THE PHOSPHORUS REQUIREMENTS

OF ROOT CROPS

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By

Peter Vander Zaag

Dissertation Committee:

Robert L. Fox, Chairman
Ramon S. de la Pena
Haruyoshi Ikawa
Roy Nishimoto
Goro Uehara

We certify that we have read this dissertation and that in our opinion it is satisfactory in scope and quality as a dissertation for the degree of Doctor of Philosophy in Agronomy and Soil Science.

DISSERTATION COMMITTEE

Robert L. Fox
Chairman

Roy K. Nishimoto

Ramon A. de la Peña

H. Ikawa

Goro Uehara

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ABSTRACT

The objectives of this study were: to determine the external and internal P requirements of five root crops (cassava, potatoes, sweet potatoes, taro and yams); to test a methodology for transferring soil management information from one site to another and to determine the phosphate fertilizer requirements of soils which have been used or have potential for growing root crops.

In order to fulfill these objectives, P experiments were identified in 10 countries. Soil samples and the field experimental data were secured. This was supplemented with experiments in Hawaii for each of the five root crops. All analytical work on the soils was done in Hawaii. P sorption curves were developed from which it was possible to predict the initial level of P established in solution and to convert each P fertilizer treatment to P in solution. The procedure used to determine P sorption curves consists of equilibrating 3 g samples of soil for 6 days at 25°C in 30 ml of 0.01 M $CaCl_2$ containing graded amounts of $Ca(H_2PO_4)_2$. The samples were shaken for 30 minutes twice daily. Crop yields were plotted as a function of the P concentration in solution. From these curves the external P requirements were determined.

Yield responses for the five root crops varied considerably. A composite yield response curve for seven experiments revealed that cassava has an external P requirement of 0.005 ppm--the lowest of the five root crops studied. This low P requirement was attributable

not only to a very extensive root system but also to a mycorrhizal association which allow for a greatly increased surface area through which diffusion of P into the roots could take place. Three experiments did not conform to the above results. In two of these experiments, foliar analysis indicated that P nutrition was inadequate at soil concentrations which would have been adequate elsewhere. These data suggest some factor, perhaps related to inefficient mycorrhiza, was responsible for these anomalous results.

Yam results were obtained from five locations. Only in Hawaii was a response to P evident and that for high yield potential varieties. The external P requirements were from 0.01 to 0.02 ppm. The roots were highly mycorrhizal suggesting that the mycorrhiza were responsible for the efficiency of yams in utilizing P at relatively low solution concentrations.

Based on results from three locations, sweet potatoes responded gradually to increasing levels of solution P. Seventy-five to 80 percent of maximum yield was obtained at 0.003 ppm P while 95 percent of maximum yield was not obtained until a P concentration of 0.1 ppm in solution was reached.

Results for three taro varieties were obtained in Hawaii. The first increments of P produced a pronounced response. The indicated external P requirement was 0.02 ppm. The taro root system was extensive but few roots developed mycorrhizal associations.

Based on results from five experiments, potatoes have a high (0.2 ppm) external P requirement. The lowest P level employed (0.003 ppm) was associated with 42 percent of maximum yield.

Based on the results of this study, it appears that P sorption curves can be used as a basis for transferring information about P fertilizer requirements from one geographic location to another irrespective of differences in sorption capacity. A survey was made of the P status of more than 300 soils from 20 countries. The various root crops seem to lie within fertility boundaries. Careful consideration should be given to the P fertilizer requirements for prospective soil-crop combinations prior to bringing new root crops into areas where they have not been grown. Phosphate sorption curves are useful tools for making predictions about phosphate fertilizer requirements in areas where detailed experimentation has not been done.

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PART I

GENERAL INTRODUCTION

In the tropics high population growth rates are creating pressure on the land for increased food production. However, in these parts of the world the systems of farming are traditional with little or no fertilizer inputs. In West Africa, the traditional shifting cultivation pattern exists which includes a period of 2 to 3 years of crop production after clearing the land followed by a 5 to 10 year fallow period. Under these conditions Africa is no longer producing the required amount of food to feed her people. She needs aid for increased production per unit of existing farm land and to develop new areas which may be marginal in nature, thus needing special management considerations.

One of the major inputs needed for increased food production is phosphate fertilizer. There is considerable diversity among the soils of the tropics as to their P requirements. In discussing the P requirements of crops on soils, various considerations are needed. However, it is now clear that the immediate source of P for the plants growing in soils is the P in the soil solution (Fox and Searle 1978). Furthermore, a close relationship exists between P in the solution and P in the sorbed state; the quantity of P sorbed varies directly with the concentration of P in solution. This information can be used to plot a P sorption curve as outlined by Fox and Kamprath (1970).

Mineralogy and texture are the major soil factors influencing P sorption. P sorption by soils can be ranked in this order: quartz = aluminum free organic matter < 2:1 clays < crystalline oxides of iron and aluminum < amorphous oxides of aluminum and iron (Fox and Searle 1978).

Mechanisms for P sorption are related to the charge characteristics of soil colloid surfaces (Mekaru and Uehara 1972). Whereas colloids of soils which are relatively unweathered are predominantly of the constant charge type, those of highly weathered soils are predominantly of the variable charge type (Mekaru and Uehara 1972). The dominant variable charge colloids are the hydrated oxides of aluminum and iron. A possible mechanism for P sorption is that the phosphate replaces hydroxyl ligands to become chemi-sorbed to the hydrated oxide surface (Fox and Searle 1978).

Other factors also influence P sorption. Time, temperature, water content, mixing, supporting electrolyte, soil pH, competition for adsorption sites, desilication of soils and surface area for adsorption are all important and are discussed in detail by Fox and Searle (1978).

Soils with high P sorption along with low concentrations of P in solution would need large applications of P fertilizers to assure optimum yields for certain crops. The cost of the P fertilizer is a major barrier to the small farmer in utilizing the required amounts for optimum yields. This would not appear to be feasible economically. However, recent investigations have shown that there is a high residual efficiency of applied P fertilizers under certain circumstances (Fox et al. 1968). Recent unpublished data by R. L. Fox indicates that plots which have been fertilized for 8 years to establish and re-establish 10 levels of P in the soil solution now require little or no fertilizer, above that which is being removed by the crop, to maintain the desired levels in solution. Thus the initial costs of a large quantity of P fertilizer can be amortized over many years.

The concept of band placement of fertilizer in improving the efficiency has been put forth in theory by Wijk (1963). However field experimentation has given indifferent or negative results (Kratky and Tamimi 1974). Studies by Fox and Kang (1978) indicate that P fertilizer placement in soil gives little promise of substantial monetary savings in fertilizer costs if yields are kept near the maximum attainable, although there may be savings when sub-optimal quantities of P are used.

The phosphorus requirements of crops have received much attention. Thousands of isolated experiments have been carried out. However, these results have very limited value as each site has different soil conditions and levels of P. These types of experimental results are very site specific unless the soil has been characterized by one means or another. This has led to the use of soil tests for P in many countries.

Soil Phosphorus Tests

Many methods have been proposed for evaluating soil phosphorus availability to crops in recent years. Most of these tests apparently have a common characteristic of limited adaptation over a wide range of soil conditions. Lawton et al. (1947) and Rudd and French (1976) found a poor correlation between various soil P extractants and the yield response of various crops to P fertilizer on various soils with different textural and drainage properties. Smith and Cook (1953) and Bishop et al. (1974) obtained a good correlation between yield and P extracted. It appears that a good correlation between soil test values and yields can be obtained for a specific region with similar soils. However, when comparing diverse soils, soil tests are of little value (Lawton et al. 1947).

Van Der Paauw (1971) reports a good correlation between a water extractant soil test and percent P in shoots of wheat for diverse soils from Australia, Britain, the Netherlands and the USA. The correlation for potatoes was not so good for the same soils but still satisfactory. Such factors as organic matter, particle size, $CaCO_3$, pH, P sorption capacity and other factors related to the origin of the soil did not affect the correlation between the water extractant soil test and the percent P in the wheat shoots.

Soil P extractants, such as the Bray 1 and Olsen methods, may indicate if P fertilizer is required but do not predict the amount of P fertilizer that is required for a specific crop. Beckwith (1964), Ozanne and Shaw (1968) and Fox and Kamprath (1970) have used P sorption curves to estimate P fertilizer requirements for crops. A major advantage of P sorption curves over the other methods is their ability to estimate fertilizer requirements directly from the sorption curve.

Studies in Hawaii suggest that P sorption curves can be used as the basis for transferring information about P fertilizer requirements from one geographic location to another, irrespective of differences in sorption capacity. Fox et al. (1974) showed that corn growing on two soils which had different sorption capacities nevertheless had the same requirement for adjusted levels of P in solution. Although the results obtained so far are promising, further testing is needed to see if P sorption curves can be generally used to predict fertilizer P requirements for crops on various soils.

External Phosphorus Requirements of Crops

There are numerous soil and crop management factors which influence the external (soil solution) P requirements for a certain crop. Peaslee and Fox (1978) discuss some of these. Some soil factors are:

1. Buffering capacity of the soil and the quantity of labile P.

2. Cross-sectional area for diffusion of P to roots and tortuosity of the diffusion path (Olsen and Watanabe 1963).

3. Soil factors associated with root development, especially root hair proliferation and mycorrhizal associations which are particularly beneficial for plant growth on P-deficient soils. The mycorrhizal hyphae provide increased surface area through which the diffusion of P can take place (Tinker 1975, Mosse 1973, Sanders and Tinker 1973).

4. Mineralization of organic P.

5. Species and concentration of salts in the soil solution.

6. Temperature.

7. Nature of the solid-phase P as this influences the rate of dissolution of P compounds.

Some plant factors include:

1. Yield potential.

2. Effectiveness of roots and associated mycorrhiza in P uptake.

3. Interaction of roots with solid-phase P.

4. Threshold P concentration for P uptake by roots.

5. Solution concentration at which roots are saturated with respect to P uptake.

6. Differential uptake of cations by plants.

Management factors include:

1. Volume of soil fertilized and placement of fertilizer with respect to roots.

2. Time of fertilization in relation to expected utilization.

Root Crops

Root crops have provided a major source of calories and protein during the ages and today remain as important suppliers of food for the growing world population. Wheat, rice and maize are the three major food crops in the world with production over 300 million tons for each of them. However, of the seven major food crops in the world, three of them are root crops, including potatoes, sweet potatoes and cassava (Harlan 1976). Potato production is predominant in the temperate zone with only 25 percent of the total production being outside of North America, Europe and the USSR. Sweet potato production is primarily in Asia with China having 75 percent of the world's production. Cassava is distributed over three continents. Yams predominate in West Africa while taro is found in Africa, Asia and Oceania. The worldwide average yields of root crops (Table 1) are low in comparison with yields obtained under experimental conditions. There is a great potential for increased production per unit area if improved agronomic techniques are adopted. Little work has been done on improved production of root crops with the exception of the potato. Only in recent years have international centers focused on root crops. In contrast cereal crops have received attention for many years and average yields have increased accordingly.

Root crops have a high biological efficiency as the edible portion is not in need of structural support whereas cereals need to devote a substantial proportion of the mass of the plant to support the edible portion (Coursey and Haynes 1970).

Table 1

Estimated Area and Production of Some Root Crops*
(Values given are millions of hectares and metric tons.)

	Potatoes		Sweet Potatoes		Cassava		Taro		Yams	
	ha	tons	ha	tons	ha	tons	ha	tons	ha	tons
World	21.90	294.00	19.26	134.23	11.88	104.89	0.76	4.36	1.99	19.22
Africa	0.41	3.30	5.48	6.19	6.57	47.54	0.67	3.40	1.93	18.64
Central America	0.07	0.66	0.12	0.70	0.12	0.75	-	-	0.02	0.23
South America	0.92	8.17	0.27	2.78	2.61	34.05	-	-	0.02	0.10
Asia	5.17	52.03	13.23	123.30	2.56	22.33	0.06	0.70	0.01	0.06
Oceania	0.04	0.91	0.11	0.57	0.02	0.22	0.03	0.26	0.01	0.19

* Data derived from FAO Production Yearbook 1974.

In this study attention will focus on the five root crops listed in Table 2.

Table 2

The Major Root Crops, Their Scientific and Common Names and Estimated Area of Origin*

Crop	Scientific Name	Other Names	Origin
Potatoes	_Solanum tuberosum_	"Irish potato"	Andes - S. America
Sweet Potato	_Ipomoea batatas_	"yams"	lowland - S. America, meso America
Cassava	_Manihot esculenta_	"manioc"	lowland - S. America, meso America
Yams	_Discorea_ (genus)		
	D. rotundata	"white yam"	West Africa
	D. alata	"greater yam" "water yam"	mountain area - Burma, China
	D. esculenta	"lesser yam" "Chinese yam"	near Irraweddy, Salween and Mekong rivers
Taro	_Colocasia esculenta_	"coco	Southeast Asia

* Information derived from: Harlan, Jack R. 1976. "The Plants and Animals that Nourish Man," Scientific American, Sept. (1976), 89-97.

OBJECTIVES

1. To determine the external and internal P requirements for five root crops on various soils.*

2. To develop means for transferring soil management information from one site to another.

3. To determine the phosphate fertilizer requirements of some soils which are being used to grow root crops or have potential for growing root crops.

* The external P requirement is defined as the P concentration in soil solution required for 95% of maximum yield.

The internal P requirement refers to the P content in a certain leaf tissue which is associated with 95% of maximum yield.

GENERAL MATERIALS AND METHODS

Procedures for Objective 1

There were two general approaches for Objective 1.

A. Field experiments using several levels of P for all five crops were carried out in Hawaii. At the Kapaa Research Station, Kauai, a Typic Gibbsihumox was used with 10 levels of P ranging from 0.002 to 1.6 ppm in soil solution which were adjusted after each crop to the desired levels. Similar plots at Poamoho (Tropeptic Eutrustox) were also utilized.

B. Existing data on root crops from P experiments recently carried out by International or National Agencies in the tropics were utilized. Suitable experiments were identified by searching the literature and by visiting institutions in the tropics.

1. Locations were identified with valid curves of yield vs. P fertilizer applied. Experiments that were utilized had acceptable cultural practices and yields appropriate for the location.

2. Data required were:

   (a) P fertilizer rates used;

   (b) yields obtained for each level of P applied;

   (c) method in which P was applied.

3. A soil sample was obtained which represented the check plot (no P added or a sample which represented the conditions of the check plot with respect to P). This soil sample was used to determine that soil's P sorption curve with which we could

convert the P fertilizer rates applied (kg/ha) to equivalent values of P concentration in solution.

4. Relative yield against equivalent P in soil solutions were plotted; from this the external P requirement was determined for each crop on the various soils. Also, from the sorption curve, the P status of that soil and its capacity to sorb P were determined.

In meeting Objective 1 the following number of experiments were located: potatoes, 7 experiments; sweet potatoes, 3 experiments; cassava, 10 experiments; yams, 5 experiments; and taro, 1 experiment.

Internal P requirements were obtained from the experiments in Hawaii and also from some of the other existing experiments. The time of sampling and index tissues used are given in Table 3 for each crop.

Table 3

Index Tissues and Time of Sampling for Determining Internal P

Crop	Tissue	Time after planting
Cassava	1st fully matured leaf blade and petiole	5 months
Potato	1st fully matured leaf blade and petiole	60 days
Sweet Potato	1st fully matured leaf blade and petiole	80 days
Yams	1st fully matured leaf (blade and petiole intact)	4-5 months
Taro	1st fully matured leaf blade	3 months

Procedures for Objective 2

For each crop the results of the field experiments were examined to see what relationships could be found between productivity, P requirements and the soil as classified. Soil, plant and management factors were also considered in trying to develop relationships between productivity and P requirements (ppm in soil solution) for the various root crops.

Procedures for Objective 3

The P sorption curves developed for attaining Objective 1 were used as a basis for comparing other soils. Methods frequently used for evaluating the P status of soils were compared with yield data generated by these experiments and with P requirements as estimated from phosphorus sorption curves.

Anticipated Results (from all three objectives)

1. Knowledge of the external P requirements of these five root crops will permit estimation of P fertilizer requirements from soils data.
2. Knowledge of the internal P requirement of these five root crops will permit evaluation of whether or not soil fertilization with phosphorus was adequate.
3. Data from one experimental location can be transferred to other locations using P sorption curves as the basis for transfer.
4. Information about productivity and crop response can be transferred from one location to another based on soil classification information.

5. Data will contribute to developing a soil phosphorus atlas or map for the tropics.

Laboratory Methods

Procedure for determining P sorption curves. The procedure for determining P sorption curves was that of Fox and Kamprath (1970). Three gram samples of soil were equilibrated for 6 days at 25°C in 30 ml of 0.01 M $CaCl_2$ containing graded amounts of $Ca(H_2PO_2)_2$. Two drops of toluene per sample were added to retard microbial growth. The samples were equilibrated in 50 ml plastic centrifuge tubes shaken longitudinally in a reciprocating shaker for 30 minutes twice daily. Centrifugation was in a super-speed centrifuge and P was determined colorimetrically in the supernatant solution. Phosphorus which disappeared from solution was considered to have been sorbed. Phosphorus sorbed was plotted against P in the supernatant solution.

Procedures for determining extractable phosphorus. The Bray and Kurtz No. 1 method consisted of: a soil-solution ratio of 1:7 with the extractant being 0.025 N HCl + 0.03 N NH_4F. They were shaken longitudinally for 5 minutes at 120 reciprocations per minute in centrifuge tubes and then centrifuged. P was determined colorimetrically in the supernatant solution.

Olsen extractant consisted of a 0.5 M $NaHCO_3$ with the pH adjusted to 8.5 with NaOH. Polyacrylamide was added at the rate of 0.5 gram per liter of solution to reduce the color in the extract due to dissolved organic matter (Banderis et al. 1976). The samples were shaken for 30 minutes at 120 reciprocations per minute in centrifuge tubes, filtered and P was determined colorimetrically in the filtrate.

Double acid (Melich or North Carolina) extractant consisted of a solution of 0.05 N HCl + 0.025 N H_2SO_4. The soil solution ratio was 1:4. After shaking for 5 minutes at 120 reciprocations per minute, the samples were centrifuged and P was determined in the supernatant solution.

In all cases, P color development was by the ascorbic acid method proposed by Watanabe and Olsen (1965).

Tissue analysis. Foliar and root analyses were done by one of the following three methods: X-ray fluorescence, wet digestion with 2:1 nitric perchloric acid (Blanchar et al. 1965) or by dry ashing in a muffle furnace at 550°C overnight. The nutrients were determined by atomic absorption spectrophotometry, flame photometry, colorimetrically or turbidimetrically as appropriate.

PART II

CHAPTER I

THE PHOSPHORUS REQUIREMENTS OF POTATOES

INTRODUCTION AND LITERATURE REVIEW

The need for adequate fertility for high yields has long been recognized. A potato tuber yield of 27 T/ha removes an estimated 134-179 kg N, 28-34 kg P_2O_5 and 224-280 kg K_2O per hectare (Black and White 1973). Pronounced yield responses to P have been reported in Sri Lanka, India and Ecuador by de Geus (1973), in Canada by MacKay et al. (1966) and Bishop et al. (1967) and in the USA by Laughlin et al. (1974). Bishop et al. (1974) studied the relation between soil test values and P fertilizer responses at 18 locations in Nova Scotia, Canada. Yield responses to applied P were relatively small when soil P test values by Bray 2 and Olsen methods exceeded 225 and 75 ppm, respectively. These are very high P levels by any standard. Bray 2-P levels of 60-100 ppm gave relative yields of 50-74 percent of maximum.

There has been extensive research done on the internal P requirements of the potato. MacKay et al. (1966) indicate that 0.45 - 0.50 percent P at 60-70 days after planting in the most recently matured leaf blade is the critical level for optimum yields. Black and White (1973) indicate that 0.35 - 0.45 percent P at the early bloom stage in the first fully matured leaf blades is needed for optimum yields.

Presently there is extensive research towards adapting the potato to the lowland Tropics both by the International Potato Center and by national institutions in various tropical countries but the requirements of the potato for P under tropical conditions has not received much attention.

The objectives of this study are to compare the external and internal P requirements of the potato in the temperate and tropical zones. Then comparisons were made using potato yield data from field experiments performed in Bangladesh (Noakhali), Canada (Ontario), Peru (Huancayo), and USA (Alaska, Idaho and Hawaii--Kauai and Wahiawa).

MATERIALS AND METHODS

Wahiawa and Kauai Experiments

At both locations existing experimental plots were used which had 10 levels of P established in 1971 in an augmented block design (Federer 1956). The plots were cropped repeatedly and refertilized before each crop to re-establish the 10 desired levels of P (0.002, 0.003, 0.006, 0.012, 0.025, 0.05, 0.1, 0.2, 0.4 and 1.6 ppm in solution). The P fertilizer requirements to establish these levels of P in solution were obtained using the P sorption curve technique of Fox and Kamprath (1970). For the Wahiawa site, P sorption curves for each of the 10 treatments are given in Figure 1.1 prior to refertilization for the potato crop. The P requirement to bring treatment seven back to 0.1 ppm is approximately 40 µg P/g of soil. In this way all 10 treatments are re-adjusted before each crop. In the Kauai experiment the P plots were split with the pH adjusted to 5.8 on one half of each plot with $CaSiO_3$ (slag) and on the other one half with $CaCO_3$ (lime). The P fertilizer along with 90 kg N/ha as urea and potassium (for Kauai only) were broadcast and thoroughly tilled into the surface 15 cm of soil. At 5 weeks after planting

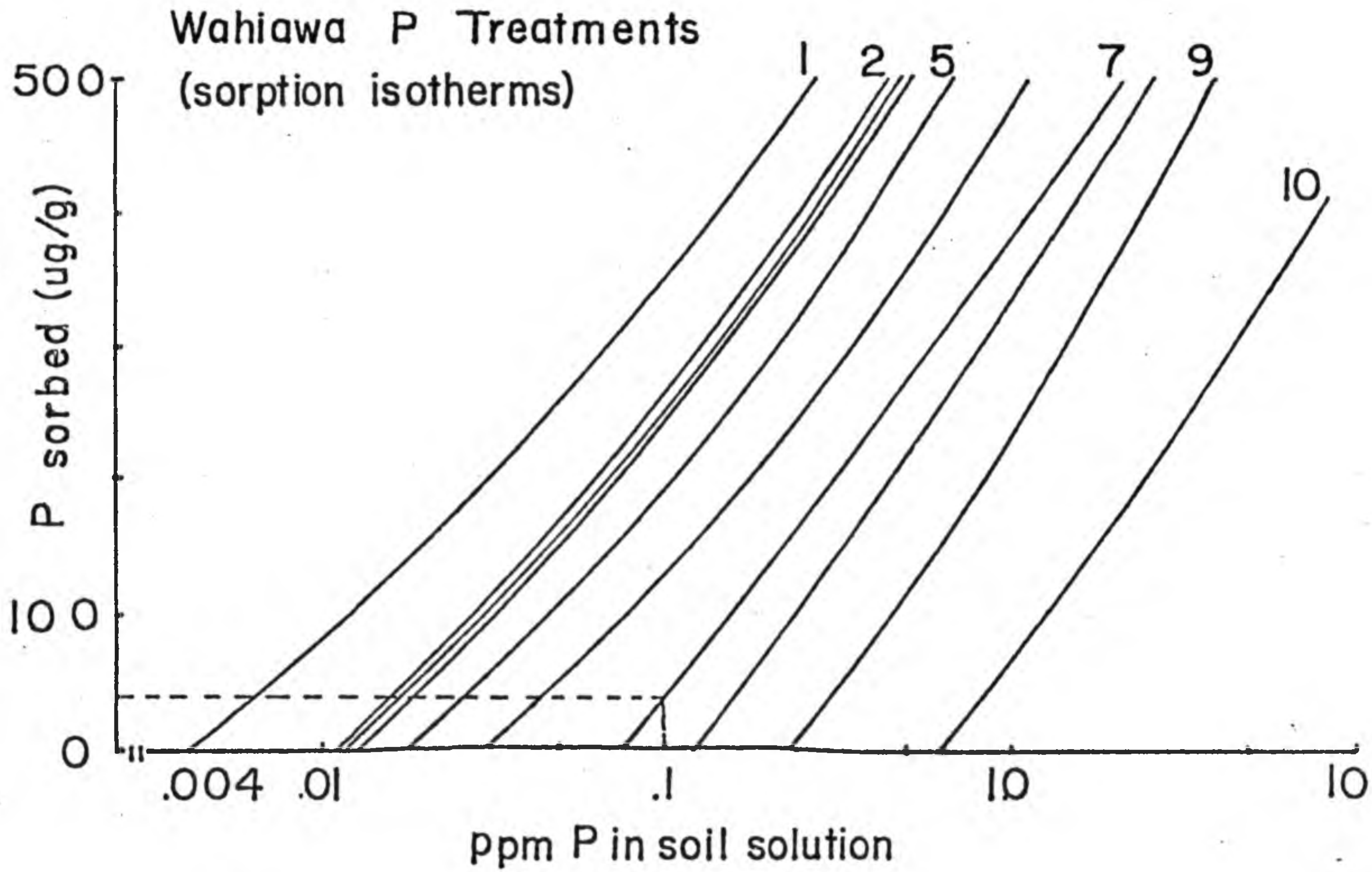


Figure 1.1 P sorption curves for each of the 10 treatments in the Wahiawa experiment prior to refertilization

another 90 kg N/ha was applied as urea.

Non-certified Russet Burbank potatoes were planted at both locations during January 1976. The seed pieces were cut to 60-80 grams in size and treated with benlate and captan. Most recently matured leaf blade and petiole samples were taken at 58, 79 and 100 days after planting at Wahiawa and at 58 and 100 days after planting at Kauai. The growing season was 127 days at Wahiawa and 110 days at Kauai.

Other Locations

Experimental data and soil samples were obtained from experiments from Alaska (Laughlin et al. 1974), Idaho (Westermann, unpublished data), Bangladesh (Ryskamp, unpublished data), Peru (Villagarcia, unpublished data), and Ontario (Van der Zaag, unpublished data). In selecting P rate field experiments from locations with such diverse soil and climatic conditions the following standards were used:

1. The number of P rates used were sufficient to define a yield response curve.
2. The highest P application rate was sufficient to permit extrapolation to 100 percent yield obtainable with reasonable confidence.
3. Cultural practices, including plant population density, water and nutrients other than phosphorus, were adequate for acceptable yields.
4. Phosphorus treatments were not confounded by other variables.
5. The field plot design included a degree of randomization and replication.

6. Soil samples (cultivated layer) representing the control (no P) plots were available.

Soil Properties

Seven locations were identified. These are listed with some details pertaining to soil classification and properties in Table 1.1.

Estimating P Levels Established in the Field

Phosphorus sorption curves were used to convert rates of P applied in the field to estimated concentrations of P in the soil solution. This procedure is illustrated for the Bangladesh soil in Figure 1.2. In the conversion from kg per hectare to μg/g, we assumed 2×10^6 kg soil per hectare, 0-15 cm depth. If soil bulk density varies significantly from the norm, the conversion factor should be changed accordingly. In the example given, the unfertilized soil supports 0.05 ppm P in solution. Phosphate applied at 35 kg/ha (Treatment Two) increased P in solution to 0.11 ppm.

Absolute yields were converted to relative yields using as 100 percent the maximum yield obtainable for each location. Relative yields vs. established levels of P in solution were plotted on a common graph.

RESULTS AND DISCUSSION

External Phosphorus Requirements

The P sorption curves presented in Figure 1.3 demonstrate that quantities of phosphate required to adjust the experimental soil to a standard concentration (0.2 ppm) in solution varied tremendously. The values ranged from 15 μg P/g for the Ontario soil to 1000 μg P/g for

Table 1.1

Some Properties of the Seven Soils Where Potatoes Were Grown

Properties	Location						
	Alaska USA	Noakhali Bangladesh	Idaho USA	Kauai Hawaii, USA	Ontario Canada	Wahiawa Hawaii, USA	Huancayo Peru
Soil subgroup	Typic Cryorthod	Aeric Haplaquept	Xerollic Calciorthid	Typic Gibbsihumox	Typic Eutrochrept	Tropeptic Eutrustox	Entisol
Mineralogy*	Quartz xxx Feldspars xx Amorphous mat'l x	Quartz xxx Feldspars x Vermiculite T Smectite T Mica T Kaolin T	Calcite xxx Smectite x Mica x Kaolin x Quartz T	Gibbsite xxx Goethite xx	Quartz xxx Smectite x Kaolin x Feldspars T	Kaolin xxx Hematite xx	Quartz xxx Vermiculite x Mica x Kaolin x Feldspars T
Soil pH	5.9	5.5	7.8	5.4	6.3	5.3	4.4
Texture:							
% clay	19	15	36	57	21	88	34
% silt	55	45	57	39	9	8	34
% sand	26	40	7	4	70	4	32
Extractable P (ppm)							
.5M $NaHCO_3$	5.6	29.7	6.7	4.6	8.1	13.0	11.4
.025N HCL+0.03N NH4F	2.2	25.0	0.1	1.1	18.6	4.0	9.0
Fertilizer P for 0.2 ppm (Kg/ha)	2000	60	85	1340	30	900	55

* Mineralogy as given includes clay, silt and sand fractions.
xxx represents >50% present.
xx represents 25-50% present.
x represents 10-25% present.
T represents <10% present.

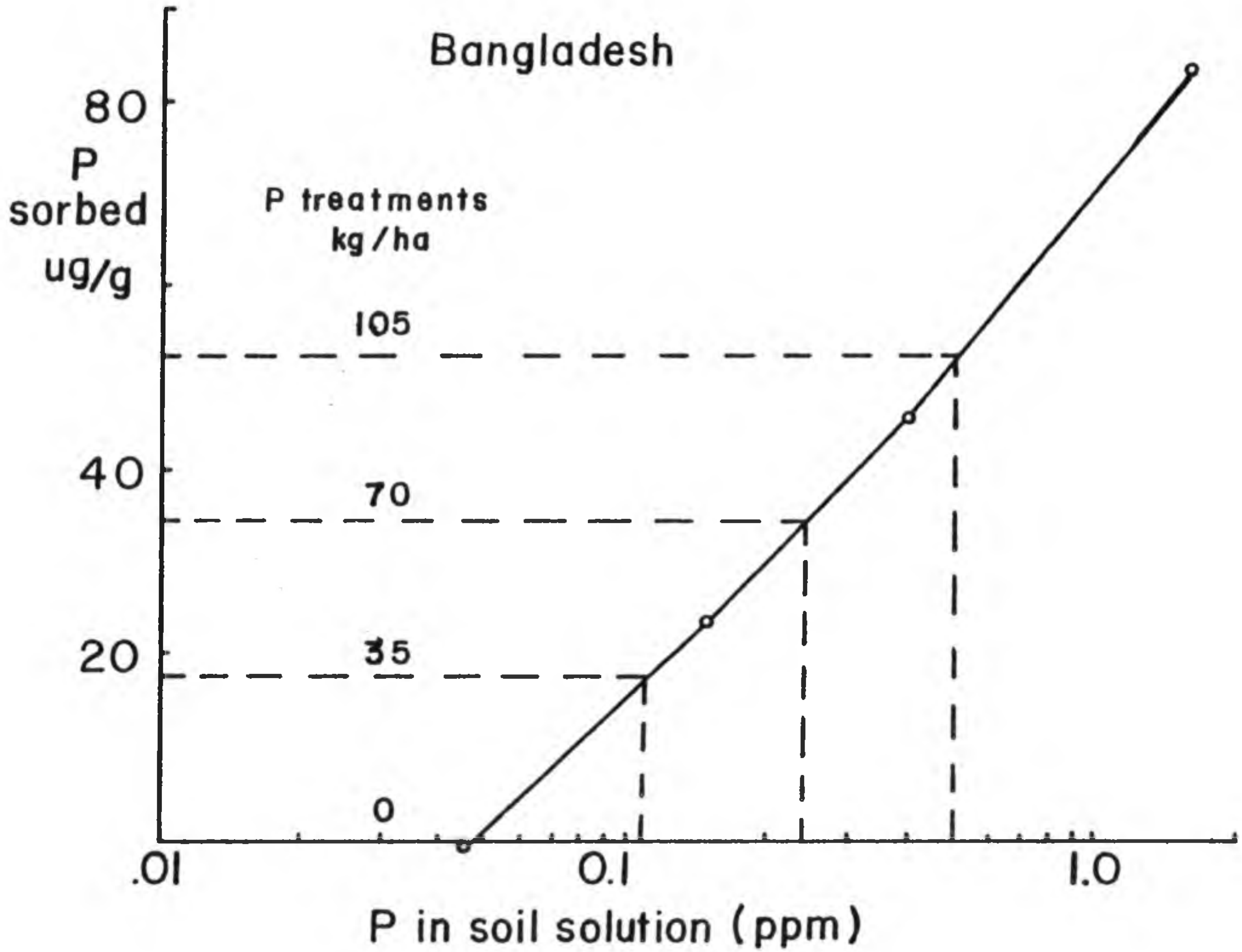


Figure 1.2 Method used to estimate the concentrations of P in solution corresponding to rates of P fertilizer applied in the field. Values for P in solution corresponding to the P fertilizer rates (zero to 105 kg/ha) were 0.05, 0.11, 0.24 and 0.5 ppm respectively. The soil is the Bangladesh Aeric Haplaquept.

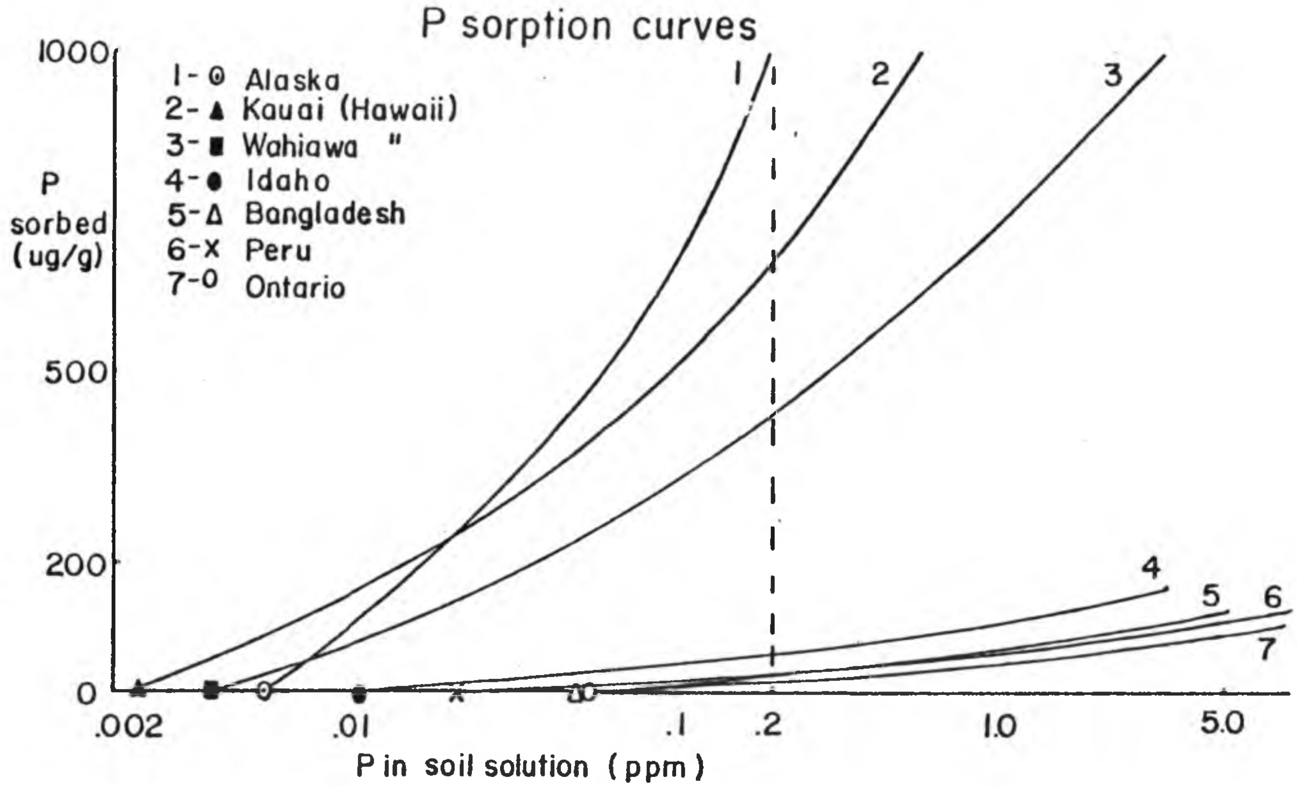


Figure 1.3 P sorption curves for the soil from seven locations showing a diversity of sorption characteristics and variable initial levels of P in soil solution.

the Alaska soil. The soils also differed greatly in the P concentrations which equilibrated with them. Values ranged from about 2 ppb for the Gibbsihumox of Kauai to 0.05 ppm for the soils from Bangladesh and Ontario.

A plot of actual and relative potato yields versus adjusted concentrations of P in solution (five locations) as presented in Figures 1.4 and 1.5 indicates a smooth curve with 95 percent of maximum yield attainable at 0.2 ppm P in solution. This is a reasonable value as compared with the requirements for several vegetable crops (Nishimoto et al. 1977). It is generally higher than the requirements for grain crops such as corn (Fox and Kang 1978).

The method which we have outlined should not be applied blindly. Deviation from the established criteria for selecting experimental data can lead to anomalous results. Two examples are presented in Figure 1.6.

The Alaska data gives no evidence that maximum yields were attained. The plot of yield versus log P in solution gave a straight line (Figure 1.6); also P in solution was in all cases below the concentration required for maximum yield (Figure 1.5). In addition, P levels in the leaf blades were less than 0.25 percent (75 days of age) which is far below the optimum level (0.5 percent at 60-70 days) required for maximum yields (MacKay et al. 1966). From the data on P requirements for potatoes based on five locations (Figure 1.5), we estimate that 0.01 ppm P in the soil solution is sufficient for only 60 percent of maximum yield. The Alaska field data combined with the phosphate sorption curve data suggest that 0.01 ppm would give a yield of 35 T/ha. By fitting these data onto the curve of Figure 1.5 and by extrapolating along the curve to 0.2 ppm, the predicted maximum yield would be about 56 T/ha.

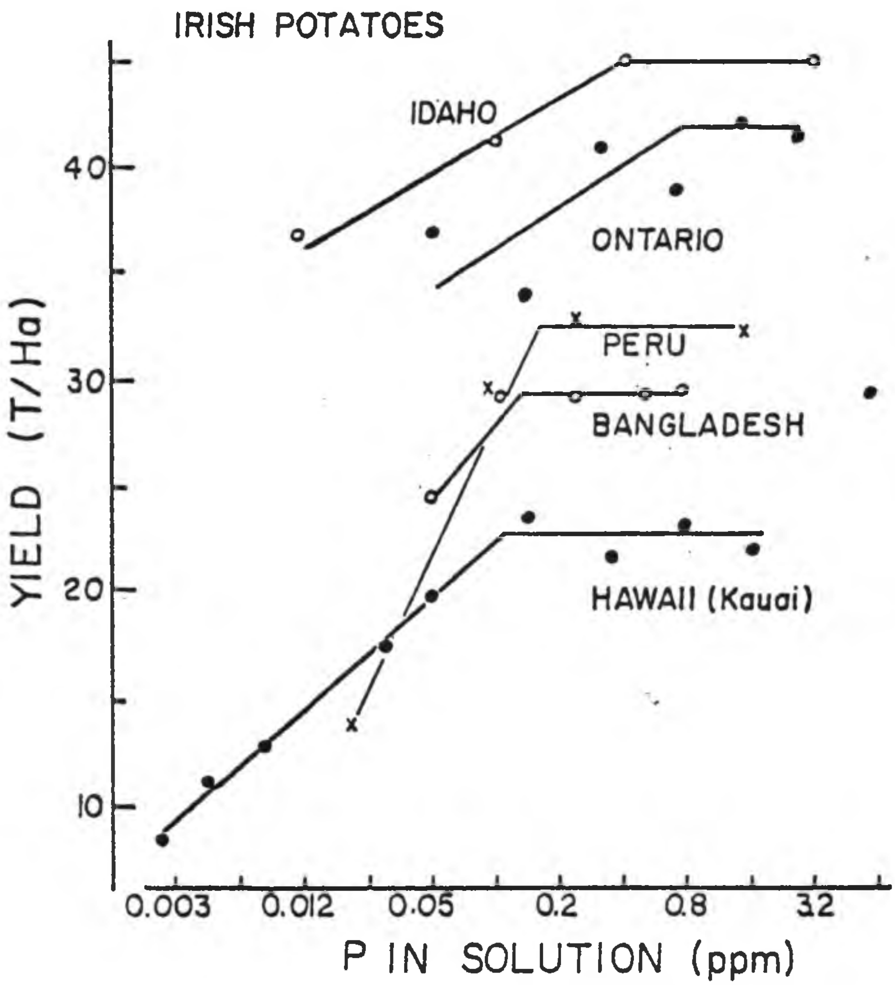


Figure 1.4 Yield of potatoes (five locations) as a function of estimated levels of P in soil solution.

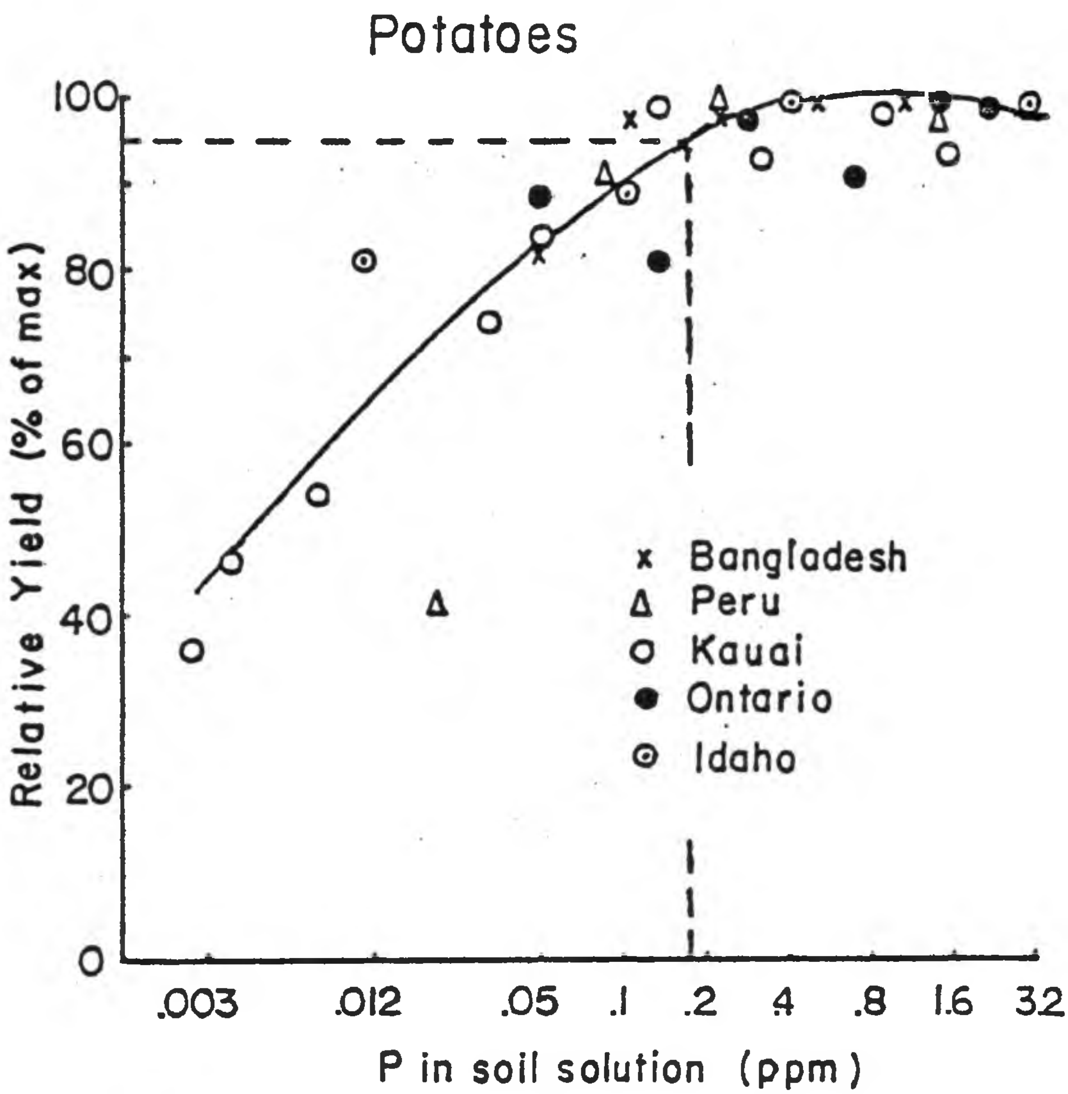


Figure 1.5 The composite yield response curve for potatoes grown at five locations as a function of P concentration in solution is described by the equation $Y = 2.0 - 6.81\ P + 61.1\ [\log(P \cdot 1000)]^{\frac{1}{2}}$ with a correlation coefficient of $r = 0.90$.

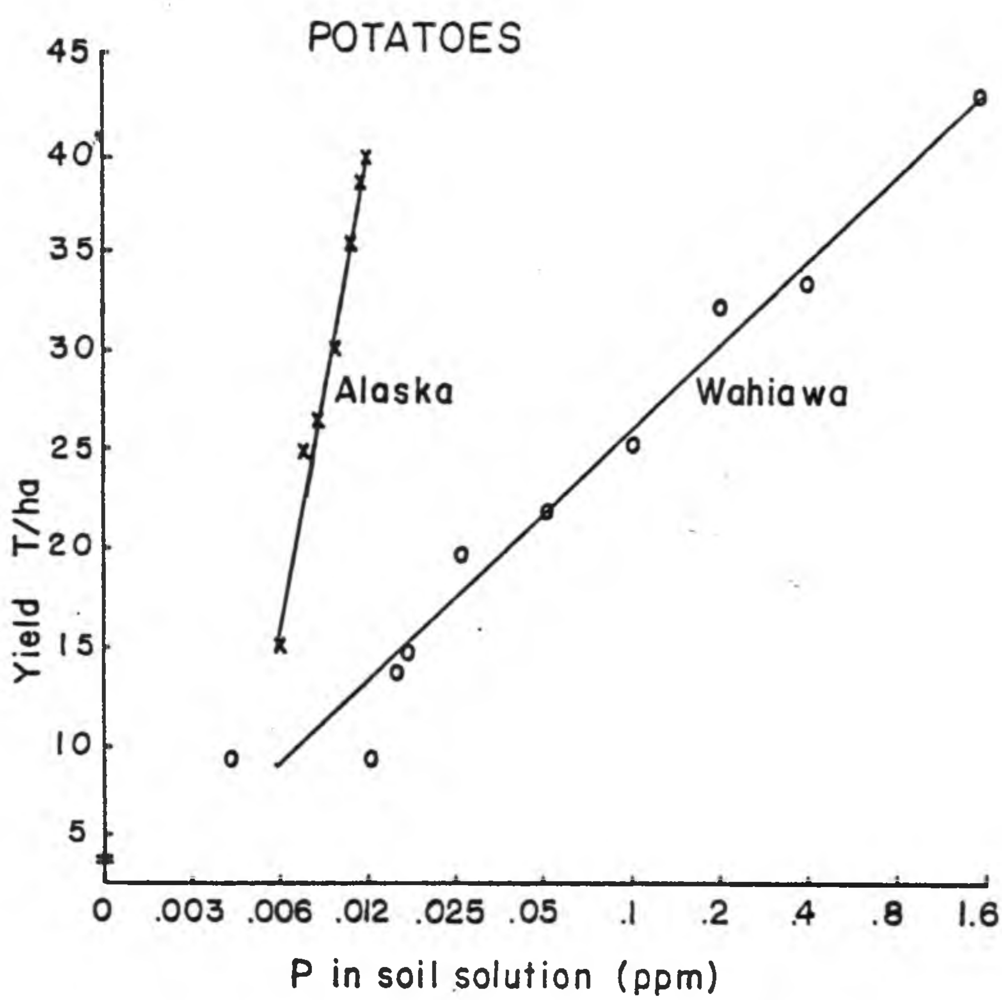


Figure 1.6 Yield response of potatoes to P for Alaska and Wahiawa (Hawaii). The correlation coefficients for yield versus P in solution were 0.97 and 0.81 respectively.

According to the P sorption curves presented in Figure 1.3, approximately 2000 kg P/ha would be required to give 0.2 ppm P in solution. Although the Alaska data does not fulfill criterion No. 2 of the procedures for selecting field experimental data, use of the data allows us to make some predictions about the yield potential of the Alaska site if the P constraint is removed.

High P requirement by the Alaska soil, as indicated by the P sorption curve (Figure 1.3) and the steep slope of the yield response curve (Figure 1.6) is in keeping with what is generally known about phosphate sorption by soils which contain weathered amorphous materials. The Alaska soil is volcanic ash affected. Mitchell and McKindrick (1975) have reported on high P retention by such soils in Alaska. Values obtained for phosphate sorption at standard concentration (0.2 ppm in solution) for the Typic Cryorthod (Alaska), and Typic Dystrandept (Costa Rica) and a Typic Hydrandept (Hawaii) were 1000, 1900 and about 2800 μg P/g soil, respectively (Table 1.1) (Fox 1974 and Fox et al. 1974).

The data from the Wahiawa location illustrates a problem encountered when there is a confounding influence of other variables--in this case, disease. Except for the high P treatments, yields were severely affected by <u>Rhizoctonia solani</u>. Under these circumstances, the highest yield was obtained at 1.6 ppm P in solution--the highest P level established (Figure 1.6). However, there was evidence from foliar analysis that P nutrition of the potato plant per se was adequate at intermediate levels of P in the soil solution. Plant P levels (uppermost mature leaf blades at 58 days) were 0.5 percent at about 0.15 ppm P in solution. MacKay et al.

(1966) have suggested that 0.5 percent P in uppermost mature leaves at 60-70 days is approximately optimum for potato production.

Internal Phosphorus Requirements

Wahiawa. The most recently matured leaf blades and petioles were sampled at 58, 79 and 100 days after planting. The samples were oven dried, ashed and P was determined colorimetrically using Bartons reagent. P levels in both petioles and blades were directly related to the P concentrations in the soil solutions (Table 1.2). With time, however, P levels declined in all treatments. The internal P requirement is around 0.5 percent in the leaf blades at 58 days after planting at the estimated external P requirement for potatoes of 0.2 ppm P in solution which agrees with the results of MacKay et al. (1966). P levels were about 20-30 percent lower in the petioles. P in the tubers also increased with increasing P in the solution (Table 1.2). Values ranged from 0.10 percent at the lowest P treatment to 0.22 percent at 0.2 ppm P in solution.

Kauai. The most recently matured leaf blade and petioles were sampled at 50 and 100 days after planting. The samples were analyzed by X-ray fluorescence for all nutrients except N. The P levels in leaf blades and petioles increased similarly to the Wahiawa experiment. However, the levels were somewhat lower (Table 1.3). At a P in solution of 0.2 ppm the percent P in the leaf blades at 58 days after planting is approximately 0.36 percent which is lower than that reported by MacKay et al (1966) but similar to levels reported by Black and White (1973). Tuber P levels were similar to those for the Wahiawa experiment.

Table 1.2

Phosphorus Levels in Leaf Blades, Petioles at 58, 79 and 100 Days after Planting and in the Harvested Tubers for the Wahiawa Experiment (measured as percent on an oven dry basis)

P Treatment (ppm in solution)	Blades			Petioles			Harvested Tubers
	58	79	100	58	79	100	
.004	.19	.24	.12	.17	.15	.10	.10
.012	.26	.20	.22	.19	.15	.13	.16
.014	.26	.24	.20	.20	.15	.13	.16
.015	.30	.25	.21	.19	.17	.13	.17
.025	.32	.28	.23	.24	.20	.15	.20
.05	.41	.30	.21	.29	.17	.14	.18
.1	.41	.32	.25	.31	.29	.17	.21
.2	.59	.37	.26	.43	.20	.17	.22
.4	.43	.42	.26	.21	.39	.20	.22
1.6	.54	.34	.34	.56	.57	.33	.19
MEAN	.37	.30	.23	.28	.24	.16	.18

Table 1.3

Phosphorus Levels in the Leaf Blades and Petioles
at 58 and 100 Days after Planting
and in the Harvested Tubers
(measured as percent on an oven dry basis)

	58 Days				100 Days					
Treatment	Petioles		Blades		Petioles		Blades		Tubers	
ppm P	L	S	L	S	L	S	L	S	L	S
.002	.14	.11	.19	.18	.09	.09	.14	.13	.13	.12
.003	.14	.14	.22	.21	.09	.08	.15	.15	.10	.15
.007	.15	.16	.25	.26	.10	.10	.18	.18	.16	.15
.03	.16	.16	.27	.29	.09	.09	.19	.18	.15	.15
.05	.17	.19	.30	.32	.11	.10	.20	.20	.17	.14
.13	.21	.23	.34	.37	.10	.10	.20	.20	.19	.16
.34	.25	.24	.36	.34	.11	.10	.21	.21	.19	.20
.72	.34	.27	.40	.42	.11	.11	.21	.23	.16	.17
1.6	.34	.31	.40	.37	.13	.13	.23	.24	.22	.23
5.5	.48	.40	.41	.46	.25	.32	.27	.30	.27	.27
MEAN	.24	.22	.31	.32	.12	.12	.20	.20	.17	.17

L = lime S = slag

Influence of P on Other Nutrients

The level of P had no influence on the K, Na, Ca and Mg concentrations in the Wahiawa experiment (Appendix Table 1). However, in the Kauai experiment the levels of Ca increased with increased P fertilization at both sampling dates (Appendix Tables 2 and 3). The concentration of Ca is lower in the Wahiawa leaf samples and this is also the case with the soil Ca level (Appendix Table 6). The Mg levels are much higher in the Wahiawa experiment both in the leaf blades and in the soil (Appendix Tables 1, 2, 3 and 6). The concentrations of Mn and Fe generally decreased with increasing P in the solution at both locations (Appendix Tables 1, 2 and 3). This is due to a dilution effect as there was increased vegetative growth with increasing P fertilization. Manganese levels increased over time reaching close to 2000 ppm in the Wahiawa experiment, yet no toxicity symptoms were observed.

Nitrogen analysis indicated that the N levels were optimum for the Wahiawa experiment but low for the Kauai location (Appendix Table 4). Jackson and Haddock (1959) reported N levels at 102 days after planting of 2.9 percent which agrees with the Wahiawa data. Heavy rains at Kauai resulted in sub-optimal N levels which is reflected in the lower tuber yields.

Tuber samples were analyzed for the Wahiawa experiment (Appendix Table 5). The levels of K decrease with increasing P levels; this could be a dilution effect as the yield also increased. The other nutrients did not appear to be affected by the level of P in the soil.

SUMMARY

Potato yield data from field experiments performed in Bangladesh (Noakhali), Canada (Ontario), Peru (Huancayo), and USA (Alaska, Hawaii and Idaho) were used to evaluate the requirements of potatoes for P. Estimates of the concentration of P in soil solution established in field soils were obtained from phosphate sorption curves plotted for the various sites. The capacity of the soils to sorb P at standard concentrations in solution (0.2 ppm P) ranged from 15 μg/g (Ontario) to 1000 μg/g (Alaska-Cryorthod). The concentration of P in a solution equilibrated with a soil to which no P had been added ranged from about 2 ppb for a Gibbsihumox of Hawaii to 0.05 ppm for soils from Bangladesh and Canada. Although rates of P applied were high, the Alaska site--a volcanic ash affected soil--gave no evidence that maximum yields were attained. Inadequacy of P fertilization was confirmed by foliar analysis. The P sorption curve for this location predicted that the P fertilizer requirement was much greater than that actually employed. This information is consistent with other information that P sorption by soils which contain weathered amorphous materials is in the range of 1000-3000 μg P/g of soil.

At one location--Wahiawa (Hawaii)--maximum yields were attained at levels of P in solution which were greatly in excess of that required for potato plant nutrition per se. Except for the highest P levels, these plants were severely affected by Rhizoctonia solani.

Yield data from the remaining five locations were plotted against estimated P concentrations in solution to give a composite yield response curve. Phosphorus concentration of about 0.2 ppm in soil solution was associated with approximately 95 percent of maximum yield.

CHAPTER II

THE PHOSPHORUS REQUIREMENTS OF SWEET POTATOES

INTRODUCTION AND LITERATURE REVIEW

Sweet potatoes are grown successfully on poor soils under low fertilizer inputs in many areas of the tropics. In particular they have shown little response to P under experimental conditions. In Puerto Rico (Landrau and Samuels 1951, Badillo-Feliciano and Lugo-Lopez 1976), the Philippines (Lantican and Soriano 1961) and Tanzania (Uriyo and Kesseba 1973) sweet potatoes did not respond to P fertilization. The response to P fertilization is more meaningful if the initial P status of the soil is known using a soil P test. Sweet potato yields in relation to soil P test data were reported by Uriyo and Kesseba (1973). They found an extractable P level of 18 ppm by the Truog method. Nishimoto et al. (1977) reported that the P requirement for sweet potatoes is very low based on a soil test. They used P sorption curves, as outlined by Fox and Kamprath (1970), and established nine levels of P ranging from 0.003 to 1.6 ppm. Seventy-five percent of maximum yields were obtained at 0.01 ppm P and 95 percent of maximum was obtained at 0.1 ppm P in solution. Rendle and Kang (1976) used the P sorption curve technique in a pot study with three varieties of sweet potatoes. They used 20 kg of soil per pot and allowed the plants to grow to maturity. They observed different responses to P among the three cultivars; the responses, however, were relatively small with 73-88 percent of the maximum yield being obtained in the unfertilized treatment (0.01 ppm P in solution).

Internal P requirements for optimum yield vary in the literature. Nishimoto et al. (1977) reported a critical level of 0.40 percent P in the most recently matured leaves 48 days after planting. Rendle and Kang (1976) reported 0.22 percent P in the leaf blades at 63 days after planting. In Puerto Rico, Badillo-Feliciano and Lugo-Lopez (1976) report 0.32 percent P in leaf blades 84 days after planting.

This chapter deals with the internal and external P requirements of sweet potatoes based on experimental data from four locations. Experimental results were obtained from Bangladesh (Nafziger 1978, unpublished data), Nigeria (de Groot and Kang 1975, unpublished data) and in Hawaii at Wahiawa (Nishimoto et al. 1977) and Kauai from plots established specifically for this study.

MATERIALS AND METHODS

Wahiawa and Kauai Experiments

At both Hawaii locations existing experimental plots were used which had 10 levels of P established in 1971 in an augmented block design (Federer 1956). The plots were cropped repeatedly and the plots were fertilized before each crop to establish P levels in solution: unamended level, 0.003, 0.006, 0.012, 0.025, 0.05, 0.1, 0.2, 0.4 and 1.6. The P fertilizer requirements to establish these levels of P in solution were obtained using the P sorption curve technique of Fox and Kamprath (1970) (Figure 1.1).

In the Kauai experiment the P plots were split with the pH adjusted to 5.8 on one half of each plot with $CaSiO_3$ and the other half with $CaCO_3$. The residual P levels prior to planting the sweet potatoes, the desired levels and the amount of Treble Super Phosphate fertilizer applied to attain these levels are given in Table 2.1. The P fertilizer along with 200 kg of potassium and 50 kg of N as urea were broadcast applied and thoroughly tilled into the surface 15 cm of soil. The variety Miyashiro was planted on January 27, 1976. Tissue samples were taken 58 and 79 days after planting. The crop was harvested on June 29, 1976.

In the Wahiawa experiment the variety Waimanalo Red was planted on June 29, 1971. Tissue samples were taken 48 days after planting. The crop was harvested at maturity on September 30, 1971.

Nigeria Experiment

De Groot and Kang (1975, unpublished data) planted an experiment on an Oxic Paleustalf (Egbeda series). The soil pH was 6.0; organic carbon was 0.70 percent. Texture analysis was 16 percent clay, 10 percent silt and 74 percent sand. Using the P sorption curve technique five levels of P were established (0.025, 0.05, 0.1, 0.2 and 0.4 ppm P) which were replicated three times (Figure 2.1). Phosphorus solubility in control plots ranged from 0.002 to 0.015 ppm. Bray 1-P levels ranged from 5 to 36 ppm (Table 2.2). The P fertilizer was broadcast and tilled into the soil at rates to give the five levels of P desired based on the P sorption curve for the soil. Nitrogen was applied at 60 kg/ha and potassium at 40 kg K_2O/ha. On May 7, 1975 the variety T_1B_4 was planted at a spacing of 75 x 25 cm. Leaf blades and petioles were sampled 63 days after planting and analyzed. Roots were harvested at maturity.

Bangladesh Experiment

Nafziger (1978, unpublished data) planted a P x K experiment using

Table 2.1

Fertility Status Prior to Planting Potatoes/Sweet Potatoes (lime plots) for the Kauai Experiment

	P conc found (ppm)	P conc established (ppm)	TSP applied (kg/ha)	me/100 g			
				K	Na	Ca	Mg
1	.002	.002	0	.22	.29	6.75	.64
2	.0025	.0035	208	.23	.27	5.91	.59
3	.0045	.007	413	.22	.39	5.95	.54
4	.0052	.03	1560	.24	.27	6.94	.67
5	.009	.05	1973	.24	.33	7.21	.71
6	.011	.13	3320	.24	.34	8.66	.71
7	.014	.34	4575	.26	.26	8.77	.74
8	.015	.72	5100	.28	.35	9.67	.85
9	.017	1.55	7070	.23	.34	10.17	.96
10	.24	5.5	7900	.26	.38	12.54	1.08

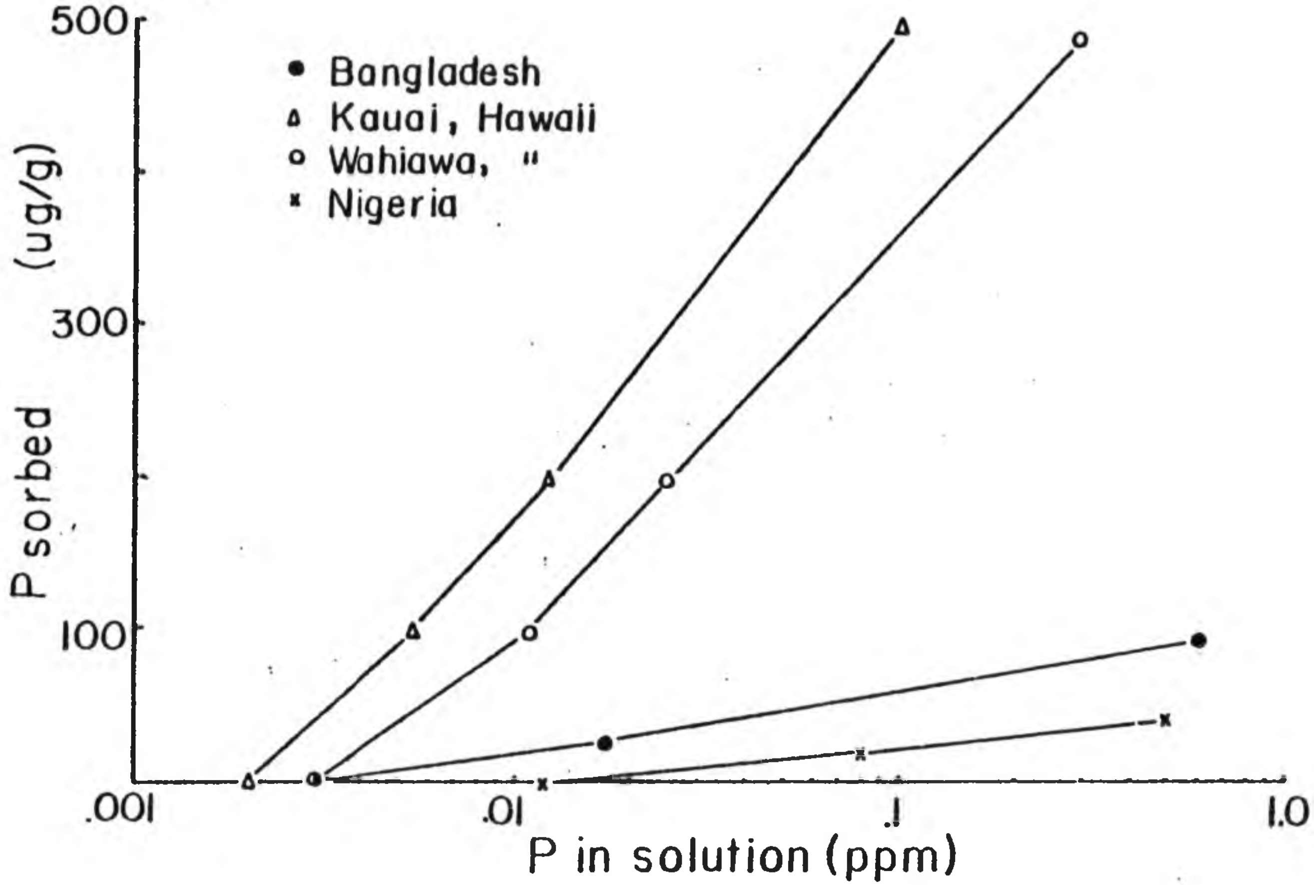


Figure 2.1 P sorption curves for the soil from four locations showing a diversity of sorption characteristics and variable initial levels of P in soil solution

Table 2.2

P Levels for the Control P Treatments
Using Three Widely Used Extractants

Location	Soil Classification	ppm		
		Bray 1-P	Double Acid	Olsen
Kauai	Typic Gibbsihumox	1	1	3
Nigeria	Oxic Paleustalf	5	-	-
Bangladesh	Aeric Haplaquept	8	14	16
Wahiawa	Tropeptic Eutrustox	2	5	10

the continuous function experimental design (Fox, 1973). Sixteen P levels ranging from 0.003 to 0.4 ppm P in solution were established using the P sorption curve technique (Fox and Kamprath 1970). Extractable P levels were higher than for the other three locations (Table 2.2). Eight levels of K were established. The experiment was replicated three times. Three applications of 67 kg N/ha were applied at planting and at 30 and 60 days after planting. The experiment was planted in early February 1978. Leaf blade samples were taken 100 days after planting. The experiment was harvested in late June.

RESULTS AND DISCUSSION

External Phosphorus Requirements

At the lowest P levels (0.003 ppm) yields were 77 percent of maximum and 95 percent of maximum yields were obtained at 0.1 ppm P (Figure 2.2). Thus sweet potatoes have a very flat yield response curve indicating its efficiency in utilizing low levels of soil P to attain near maximum yields.

Kauai experiment. Root yields ranged from 28.7 to 37.3 T/ha which are comparable to those obtained by Uriyo and Kesseba (1973). There was no significant statistical effect of the $CaSiO_3$ treatment, so the results for the two liming materials have been combined (Appendix Table 7, Table 2.3). On a relative yield basis, with 100 percent = 37 T/ha, 78 percent of maximum yield was obtained at the lowest P level (0.002 ppm). The yield response to P is small; however there was a marked vegetative growth response to P based on visual observations.

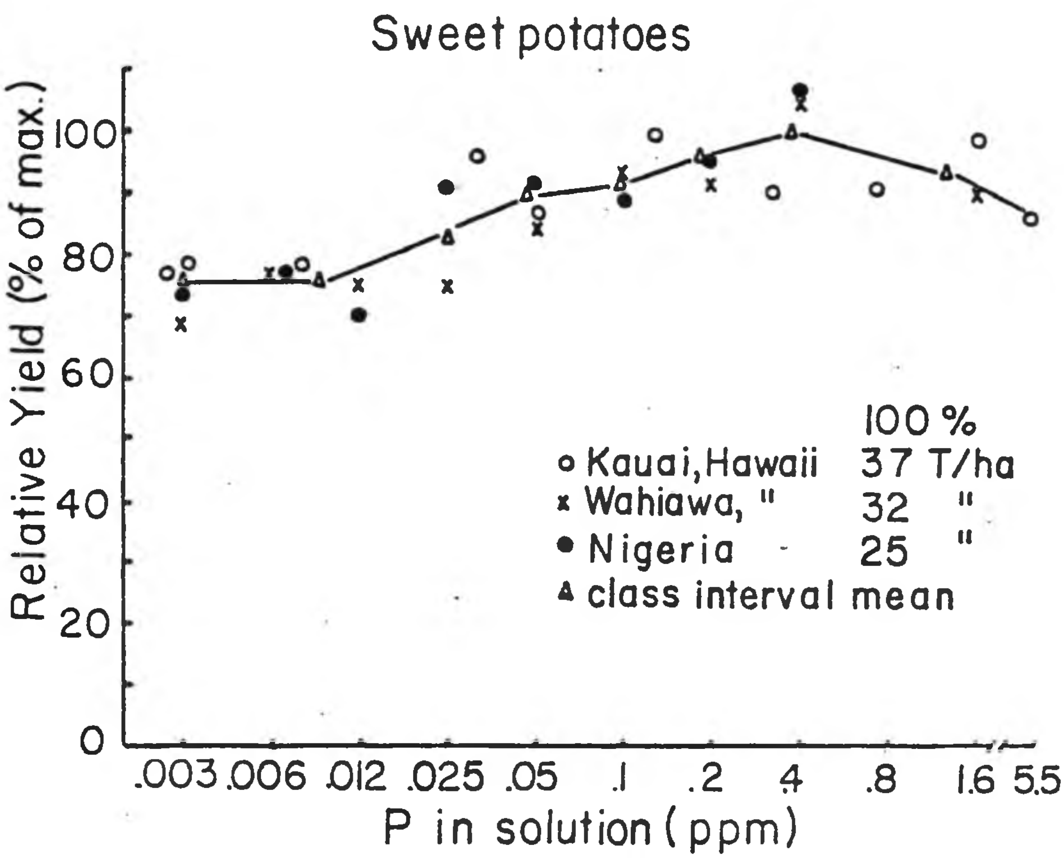


Figure 2.2 A composite yield response curve for sweet potatoes grown at three locations as a function of P concentration in solution

Table 2.3

Root Yield Response to 10 Adjusted Levels of P
in Soil Solution at Kauai
on a Typic Gibbsihumox
(Yield data is combined for lime and slag treatments)

P Treatment	P in Solution (ppm)	Yield (T/ha)	Relative Yield (100 % = 37 T/ha)
1	.002	28.7	78
2	.004	29.1	79
3	.007	29.1	79
4	.03	35.5	96
5	.05	32.4	88
6	.13	37.3	101
7	.34	33.6	91
8	.72	33.9	92
9	1.55	36.9	100
10	5.5	31.9	86

Wahiawa experiment. Root yields ranged from 22 to 34 T/ha (Table 2.4). On a relative yield basis the 0.003 ppm P treatment gave 69 percent of maximum yield. Thus a more pronounced yield response to P was shown as compared to the Kauai results.

Nigeria experiment. Yields from the five replicated treatments ranged from 22.1 to 26.8 T/ha. The control plots had yields lower than for the replicated treatments (Table 2.5). The mean yields were taken for the 0.002 and 0.003 ppm P plots and the 0.008, 0.01 and 0.015 ppm P plots. On a relative yield basis the three lowest P treatments gave yields of 70-78 percent of the maximum yield of 25 T/ha.

Bangladesh experiment. Due to flooding the root yields ranged from 3-7 T/ha, values which are not worthy for further consideration. However, internal P data is presented.

Relative yield data for the Kauai, Wahiawa and Nigeria experiments are combined to give one curve (Figure 2.2). The curve was plotted using nine class interval means. The response curve appears sigmoidal and flat. Bray 1-P ranged from 1-5 ppm for the lowest levels of P in solution which indicates that sweet potatoes utilize P very effectively.

Internal Phosphorus Requirements

In the Kauai experiment leaf blades were sampled 58 days after planting. At 79 days after planting leaf blades and petioles were sampled, combined and analyzed (Table 2.6). The internal P levels increased 200 percent from the lowest to the highest P treatments. Tuber analysis revealed that P levels also increased but only from 0.10 to 0.15 percent. The internal P levels for the leaf blades at 58 days after planting were combined for the lime and slag treatments and plotted

Table 2.4

Root Yield Response to Nine Adjusted Levels of P at Wahiawa (Tropeptic Eutrustox)

P Treatment	P in Solution (ppm)	Yield (T/ha)	Relative Yield (100 % = 32 T/ha)
2	.003	22.07	69
3	.006	24.54	77
4	.012	24.30	76
5	.025	23.76	75
6	.05	27.37	86
7	.1	29.93	95
8	.2	29.60	93
9	.4	33.79	107
10	1.6	28.84	91

Table 2.5

Root Yield Response to P on an Oxic Paleustalf
(Egbeda Series), Nigeria
(de Groot and Kang IITA unpublished data)

P Level Established ppm	Yield T/ha Replication 1	2	3	Mean	Relative Yield (100 % = 24 T/ha)
.002	25.1			} 17.8	74
.003	10.5				
.005	18.7	16.5	22.2	19.1	78
.008	18.8				
.01	18.0			} 17.3	70
.015	15.1				
.025	21.4	21.3	24.9	22.5	92
.05	19.5	23.8	25.5	22.9	93
.1	17.8	25.0	23.5	22.1	90
.2	26.3	22.9	21.9	23.7	95
.4	25.5	28.4	26.5	26.8	109

Table 2.6

Phosphorus Levels in Leaves* and Roots of Sweet Potatoes Grown on Kauai (percent on oven dry basis)

Treatment ppm P in solution		58 days			79 days			Tubers		
		Lime	Slag	Combined	Lime	Slag	Combined	Lime	Slag	Combined
1	.002	.14	.17	.16	.18	.23	.21	.09	.10	.10
2	.004	.20	.20	.20	.23	.24	.24	.10	.11	.11
3	.007	.21	.24	.23	.25	.29	.27	.11	.12	.12
4	.03	.26	.25	.26	.30	.30	.30	.11	.11	.11
5	.05	.29	.29	.29	.29	.34	.32	.13	.12	.13
6	.13	.33	.29	.31	.34	.34	.34	.11	.13	.12
7	.34	.29	.33	.31	.36	.41	.39	.13	.12	.13
8	.72	.37	.35	.36	.39	.36	.38	.13	.12	.13
9	1.55	.36	.35	.36	.34	.42	.38	.12	.14	.13
10	5.5	.38	.35	.37	.45	.42	.44	.15	.15	.15
MEAN		.28	.28	.28	.31	.34	.33	.12	.12	.12

* At 58 days leaf blades and at 79 days leaf blades and petioles were analyzed.

in Figure 2.3 along with the internal P levels from Wahiawa, Nigeria and Bangladesh. The internal P levels are high for the Wahiawa experiment. This may be partly explained by the earlier sampling date. Furthermore, Waimanalo Red is a very early maturing variety. In the Kauai, Nigeria and Bangladesh experiments later maturing varieties were grown which had similar concentrations of P in the leaf blades as a function of P in solution. It appears that 0.16 to 0.20 percent P is sufficient for 75-80 percent of maximum yield and 0.30 percent for 95 percent of maximum yield which agrees with what has been reported by Badillo-Feliciano and Lugo-Lopez (1976) but is higher than reported by Rendle and Kang (1976).

The Influence of P on Other Nutrients

Results of leaf analysis and tuber analysis are given in Appendix Tables 8 and 9. Phosphorus did not appear to influence the concentration of nutrients in either the leaves or the tubers except for calcium. Calcium concentrations increased with increased P in both the leaves and the tubers. This can be expected as the P fertilizer contains large quantities of Ca.

SUMMARY

Sweet potato yields were approximately 77 percent of maximum attainable in soils which equilibrated with 0.003 ppm P in solution (Bray 1-P of 1-5 ppm). Ninety-five percent of maximum yields are obtained at a P in solution of 0.1 ppm. The internal P requirements for 77 percent of maximum yield are in the range of 0.16 to 0.20 percent P and 0.30 percent for 95 percent of maximum yield. Sweet potatoes are very effective in utilizing low levels of P in soil solution.

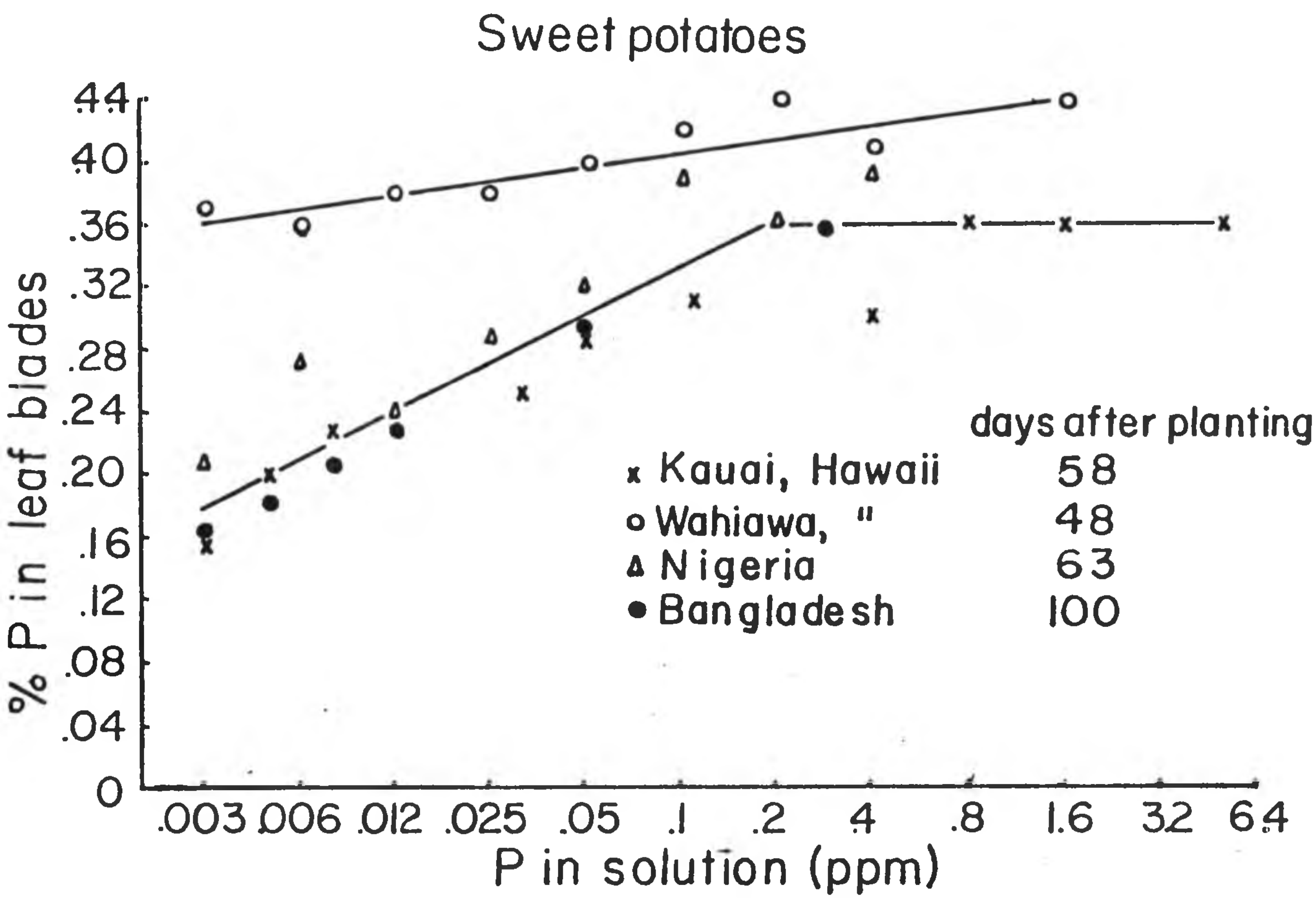


Figure 2.3 P concentration in the leaf blades of sweet potatoes for four locations as a function of P concentration in solution. The correlation coefficient for the Wahiawa data is $r = 0.89$ and for the ascending portion of the composite curve for the other three locations is $r = 0.90$.

CHAPTER III

P NUTRITION OF CASSAVA, INCLUDING MYCORRHIZAL EFFECTS ON P, K, S, Zn AND Ca UPTAKE

INTRODUCTION

The nutritional requirements of cassava (*Manihot esculenta*, Crantz) are ill-defined. It is often assumed that cassava has low nutritional requirements because it is used as the "mop-up" crop in the succession of species which make up the traditional slash-and-burn cropping system in the humid tropics. However, in some experiments cassava has responded to fertilizers containing N, P and K. For example yields of 2 of 4 cultivars tested in Sierra Leone were increased substantially as a result of P fertilization (Godfrey-Sam-Aggrey and Garber 1978). Similar results were obtained for single cultivars in the Llanos Orientales of Colombia (Howeler et al. 1976), and at Kerala, India (Vijayan and Aiyer 1969). Some typical results of field experimentation with P fertilizer have been presented by de Geus (1973). With respect to response to P fertilizer, these results were inconsistent. In fact, a frequent result of field experimentation with P on cassava is no response at all (Yong 1970, Silva and Freire 1968). However, when cassava is grown in sand culture the response to P application is large and the P requirement is high (Malavolta et al. 1955). Indeed, the concentration needed for maximum growth in flowing nutrient culture solution was in the range 1.5 to 3.9 ppm P, a value higher than those for any other species reported in the literature, with the possible exception of potatoes (Edwards et al. 1976). Thus, there are apparent discrepancies in the response of cassava to P in sand or solution cultures and results generally obtained in field situations.

The role of vesicular-arbuscular (VA) mycorrhizae in the P economy of plants is being intensively studied by many investigators. VA mycorrhizae are particularly beneficial for plant growth in P deficient soils and generally enhance the uptake of other nutrients too (Tinker 1975, Mosse 1973). This is associated with hyphal extensions into the soil beyond the depleted zone adjacent to plant root surfaces (Sanders and Tinker 1973).

This paper deals with the P requirements of cassava grown in soil and the effect of P on other nutrients both in the presence of VA mycorrhizae and in soils where VA mycorrhizae were for all practical purposes eliminated by fumigation.

MATERIALS AND METHODS

The experiments were sited on the islands of Kauai (Typic Gibbsihumox) and Oahu (Tropeptic Eutrustox). Both experiments were initially established in 1971 as part of a program to evaluate the external P requirements of important tropical crops (Fox et al. 1974, Nishimoto et al. 1977). Ten levels of P had been established in an augmented block design (Federer 1956). The plots were initially fertilized and subsequently refertilized for each crop so that P concentrations in solutions equilibrated with soil from the plots (intended P concentration in soil solutions) were approximately as presented in Table 3.1. The P fertilizer requirements to establish these levels of P in solution were obtained using the P sorption curve technique of Fox and Kamprath (1970).

Table 3.1

Levels of P Maintained and Soil Phosphate Extracted by Three Widely Used Extractants for the Experiment on the Islands of Kauai (Cultivar Experiment) and Oahu (Mycorrhiza Experiment)

P level maintained in the soil	Cultivar Experiment			Mycorrhiza Experiment		
	Bray P-1	Double Acid	Olsen	Bray P-1	Double Acid	Olsen
μg/ml	ppm on soil basis					
.002	1	<1	3	-	-	-
.003	2	1	6	2	5	10
.006	2	1	8	4	7	12
.012	6	3	16	14	20	28
.025	10	7	22	29	35	44
.05	24	11	46	55	47	68
.1	41	28	78	76	86	97
.2	55	40	96	153	156	162
.4	93	73	143	180	210	175
.8*	-	-	-	140	173	153
1.6	172	140	266	340	380	295

* This treatment was formerly the control treatment (0.002 μg/ml). Due to contamination with P, this plot was recently adjusted to give 0.8 μg/ml P. The extractable P levels were low because this treatment had only received three P fertilizer applications.

The P fertilizer was broadcast on the surface of the soil and thoroughly tilled into the surface 15 cm of soil. At the time of the cassava experiments the levels of extractable P were determined using 3 methods--Bray and Kurtz No. 1 (0.025 N HCl + 0.03 N NH_4F), Olsen (0.5 M $NaHCO_3$) and Double Acid (0.05 N HCl + 0.025 N H_2SO_4). In the experiment on the island of Kauai (cultivar experiment), the plots were split. The soil pH was adjusted to 5.8 in 1971 by applying $CaCO_3$ to one half of each plot and $CaSiO_3$ to the other half. The pH was 5.4 prior to the cassava experiment. The purpose of the $CaCO_3$-$CaSiO_3$ comparison was to see whether the silicate would make more of the applied P available (Silva 1971).

The cultivar experiment (Experiment No. 1) was planted during November 1976 with 6 cassava cultivars in one row sub-plots (1 x 0.75 meter spacing). Plot dimensions were 12.4 x 9.3 meters. Nitrogen was applied as urea at 100 kg N/ha in three applications as follows: 12.5 kg/ha at planting, 25 kg/ha at 2.5 months and 62.5 kg/ha at 5 months after planting. Potassium was applied as KCl in two applications; 200 kg/ha at planting and 25 kg/ha at 5 months of age. Foliar analysis of the upper fully matured leaf blades and petioles at 5 months of age indicated that the levels of Mg and S were low. Therefore, 500 kg/ha magnesium sulfate was applied at that time. at 12 months of age the roots were harvested, weighed and samples were taken for chemical analysis.

The mycorrhiza experiment (Experiment No. 2) was performed on the island of Oahu. The soil pH was adjusted to 5.8 with $CaCO_3$. Potassium as KCl was added to provide one meq. K/100 grams of soil. Since these plots were to be used to study the effects of VA mycorrhizae on the mineral nutrition of plants, all tillage operations, including making irrigation furrows were performed before the plots were fumigated. One half of each P treatment was fumigated with 48 g methyl bromide and 1 g chloropicrin per m^2 under plastic covers which were removed after one week. It was assumed that all VA mycorrhizae present in the fumigated soil were destroyed while still being present in the non-fumigated half of the plot. Plastic bags were used as shoe covers during plot work subsequent to fumigation to avoid contamination of plots with mycorrhizal spores. Seven crop species including cassava were planted in this experiment (Yost and Fox 1979). This experiment was planted during March 1978. Chinese cabbage (Brassica pekinsensis) was included in the experiment to demonstrate that the effect of fumigation was in fact a mycorrhizal effect. Because Chinese cabbage does not form mycorrhizal associations (Gerdemann 1968) the elimination of mycorrhiza should not be detrimental to the growth of this species.

Cassava leaf blade samples, from 18 plants per plot, were taken 80 days after planting from the youngest fully matured leaves. The plots were terminated at 120 days because VA mycorrhizal associations were present at that time on plants growing in the fumigated soils. Mycorrhizal infection was determined using the method of Phillips and Hayman (1970).

Leaf analysis for the cultivar experiment was done by X-ray fluorescence. Root samples from the cultivar experiment and all samples from the mycorrhiza experiment were digested with 2:1 nitric perchloric acid (Blanchar et al. 1965), and the nutrients were determined as follows:

atomic absorption spectrophotometry for Zn; colorimetrically for P; turbidimetrically for S (Tabatabai 1974) and by flame photometry for Ca and K.

RESULTS AND DISCUSSION

Cultivar Experiment (Experiment No. 1)

Plant height at 8 months increased from about 1.2 meters without P to about 3 meters at the highest level of P. However, even when no P fertilizer was applied the leaf canopy was continuous over the entire plot area.

Cassava root yields were less dependent on the level of P nutrition than was vegetative growth (Appendix Table 10 and Fig. 3.1). One cultivar, Ceiba, was outstanding as far as root yield was concerned. Data for that cultivar are presented separately; data for the other five cultivars were combined for presentation of yield and foliar analyses. There was no significant effect of the liming materials, so the liming treatments were combined. Ceiba produced 48 T/ha at an initially established P level of 0.025 ppm, but the yield was almost as great (42 T/ha) when no P was added. That these soils are extremely low in extractable P is evident from Table 3.1. Olsen's $NaHCO_3$ method extracted only 3 ppm P.

There was strong evidence that root yields decreased with increasing P levels in the soil solution above 0.025 ppm (Fig. 3.1). But visual estimates of vegetative growth were that vegetative growth increased with increasing P levels, being greatest at the highest P level. These observations suggest that vigorous top growth which was associated with the high P levels was made at the expense of carbohydrate storage in the

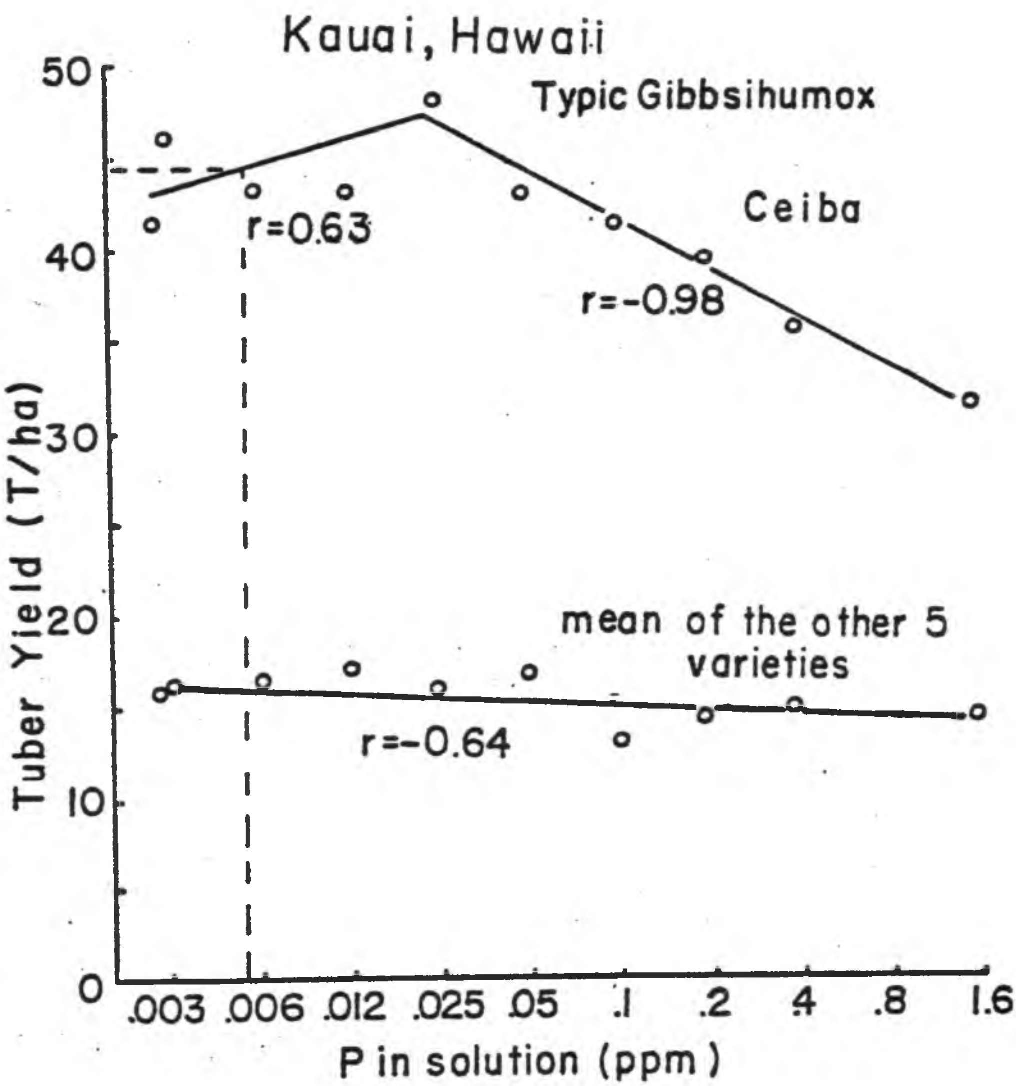


Figure 3.1 Relationship between the estimated concentration of phosphate which has been established in the soil solution and the yield of cassava in the Kauai experiment. The dashed line indicates the external P requirement for 95 percent yield for the cultivar Ceiba.

roots. Similar results have been observed with other root crops when excessive vegetative growth was produced as a result of excessive nitrogen fertilization.

Although vegetative growth of cassava increased substantially as a result of P fertilization, concentration of P in leaf blades changed very little with changing levels of P in the soil (Table 3.2). Petiole P levels increased slightly with the first three increments of P but leveled off beyond that. Considering the extremely low P levels in the soil (Table 3.1), the cassava roots were very effective in utilizing relatively insoluble P from the soil.

Table 3.3 is a summary of nutrients other than P in leaf blades, petioles, and roots at a solution P level of 0.012 ppm. Since Mg and S levels were lower than reported from Colombia (CIAT Annual Report 1975), Mg and S were applied after tissue analysis indicated these deficiencies.

The P percentages of cassava roots (Table 3.2) were in the range of 0.07 to 0.08 for all but the highest soil P levels. These values are low in comparison with other root crops for which we have unpublished data (sweet potatoes, 0.12 percent; yams, 0.16 percent; potatoes, 0.18 percent and taro 0.28 percent). Low P content of the roots suggests that cassava would be relatively insensitive to soil P level as compared with other root crops.

It is now well established that nutrient uptake by most agricultural crops is enhanced by mycorrhizal associations between roots and certain fungi. The fact that cassava is so successful in this regard led us to include this crop among seven species of plants in an investigation of the role of VA mycorrhizae in nutrient utilization from a Tropeptic Eutrustox.

Table 3.2

Phosphorus Levels in Cassava Leaf Blades, Petioles and Roots (Experiment No. 1) for the Cultivars Ceiba and the Mean of the Five Low Yielding Cultivars (on oven dry basis)

Soil P level	Leaf blades		Petioles		Roots	
	Ceiba	5 cultivars	Ceiba	5 cultivars	Ceiba	5 cultivars
μg/ml	%					
.002	.43	.38	.30	.26	.07	.08
.003	.43	.41	.31	.31	.06	.08
.006	.46	.43	.36	.34	.07	.08
.012	.43	.42	.35	.35	.07	.08
.025	.39	.43	.37	.35	.07	.08
.05	.43	.43	.37	.37	.07	.08
.1	.44	.43	.36	.35	.08	.08
.2	.45	.43	.33	.35	.08	.08
.4	.47	.43	.37	.36	.09	.10
1.6	.47	.45	.36	.37	.10	.10

Table 3.3

Nutrient Levels in Leaf Blades, Petioles and Roots of Cassava (Cultivar Experiment) at 5 Months of Age for P Treatment (0.012 ppm P in Solution)

	%					ppm			
Petioles	N	K	Ca	Mg	S	Mn	Fe	Cu	Zn
Ceiba	1.8	3.0	2.0	.25	.08	47	122	16	33
5 Var.	1.9	2.9	1.8	.31	.07	57	119	14	28
Blades									
Ceiba	4.3	1.5	1.1	.16	.20	50	157	7	26
5 Var	4.2	1.5	1.0	.19	.19	62	161	8	32
Roots									
Ceiba	-	.47	.12	.07	-	-	-	-	-
5 Var	.21	.64	.14	.06	-	-	-	-	-

Mycorrhiza Experiment (Experiment No. 2)

The effect of fumigation on Chinese cabbage was in all cases beneficial. We suppose that such benefits were due to the destruction of nematodes and other harmful soil organisms and to the Birch effect. For the two lowest P treatments, yields were increased 78 percent as a result of the fumigation. By way of contrast, fumigation depressed the growth of cassava, so that at 118 days the top growth of the fumigated treatments was only 10 percent as great as the non-fumigated treatments. We conclude that the dominant effect of fumigation was on mycorrhiza; therefore, we feel justified in referring to the fumigated and non-fumigated treatments as non-mycorrhizal and mycorrhizal treatments respectively and henceforth in this paper this terminology will be used.

Non-mycorrhizal cassava plants invariably contained less P on a percentage basis than mycorrhizal plants. Phosphorus percentage in the leaf blades increased with increasing solution P concentrations, but the over-riding effect was that of mycorrhizae (Fig. 3.2, 3.3). For example at low levels of solution P, percent P in leaves was decreased to approximately one third in the non-mycorrhizal plants. Even at the highest levels of soil P, leaf P was still decreased by one third. The mycorrhizal effects are even more dramatically evident in Fig. 3.3 which is based on P uptake. Only at high soil P levels were the non-mycorrhizal plants able to take P in amounts equal to those of the mycorrhizal plants even at the low levels of soil P.

The difference in P percent and P uptake between mycorrhizal and non-mycorrhizal plants (Fig. 3.2 and 3.3) is the net effect of fumigation. There may have been beneficial effects of fumigating cassava, as there

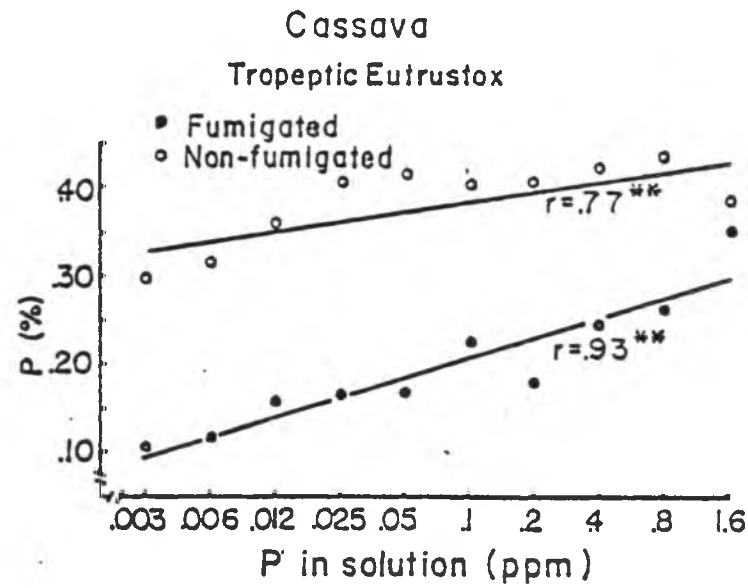


Figure 3.2 Phosphorus percentage of the leaf blades of non-mycorrhizal plants grown on fumigated plots as compared to mycorrhizal plants grown on non-fumigated plots at 10 P levels

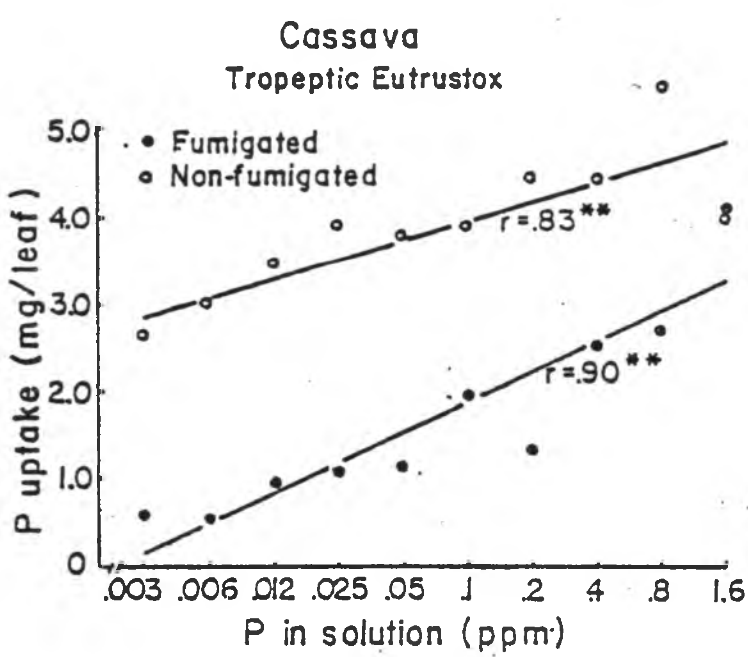


Figure 3.3 Phosphorus uptake by cassava leaf blades as affected by soil fumigation and soil P status

was in the case of Chinese cabbage. The destruction of nematodes may have enhanced root growth, and thus promoted P uptake by the plants growing on the fumigated plots. Since the net effect of fumigation was to dramatically depress P uptake, such positive components must have been strictly subordinated to the main effect of fumigation on mycorrhizal formation.

These findings give a logical explanation for the observation that P requirement for cassava in nutrient culture solutions is > 1.5 ppm while low P requirements are typically observed in the field.

The role of VA mycorrhizae in the uptake of nutrients other than P was also investigated in the experiment. The mycorrhizal plants tended to be higher in Zn than non-mycorrhizal plants, although the magnitude of the differences was not statistically significant (Fig. 3.4). The experimental site had been fertilized with Zn 7 years previously and the P fertilizers used contained some Zn as an accessory nutrient; therefore, we do not consider this a definitive experiment on Zn. Concentrations of Zn in mycorrhizal peach seedlings were 2 to 3 fold greater than in seedlings that did not form the mycorrhizal association (Gilmore 1971). At the lowest P level, S and K percentages were approximately 50 percent greater in leaves from mycorrhizal plants than in leaves from non-mycorrhizal plants. An extrapolation of the curves for S and K percent versus soil P level converged at a soil P level of about 6 ppm (Fig. 3.5, 3.6). This suggests that mycorrhizal infection does not decrease to zero until the concentration of P in soil solution exceeds 1.6 ppm. The estimated value is 6 ppm P based on the extrapolated curves. This is in keeping with our observations that mycorrhizal infections decreased but were not eliminated by the highest levels of soil P.

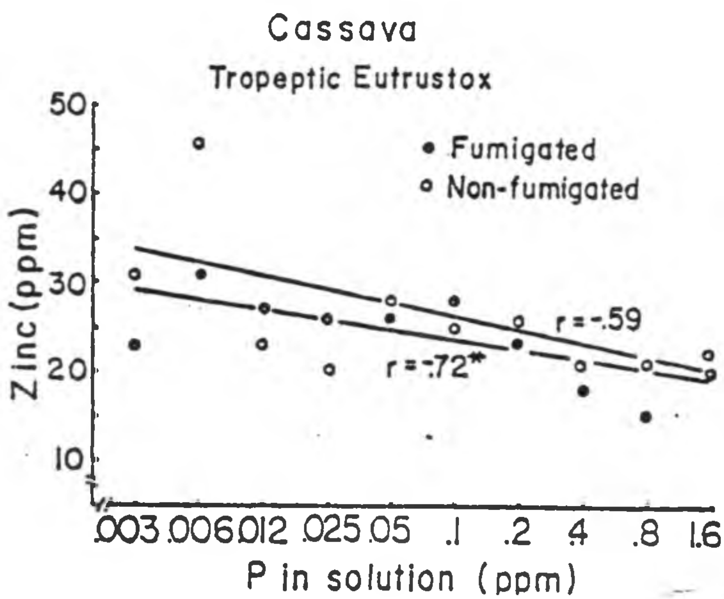


Figure 3.4 Zinc concentration in cassava leaf blades as affected by soil fumigation and soil P status

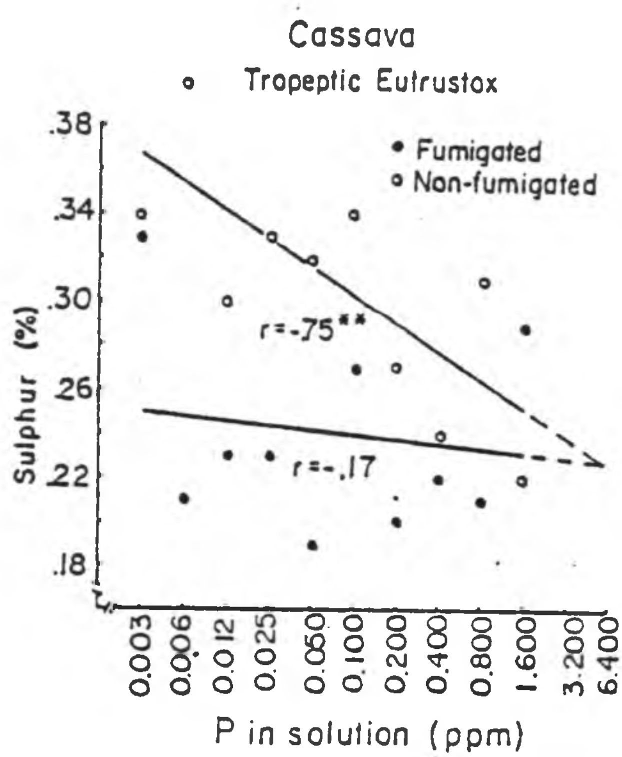


Figure 3.5 Sulphur concentration in cassava leaf blades as affected by soil fumigation and soil P status

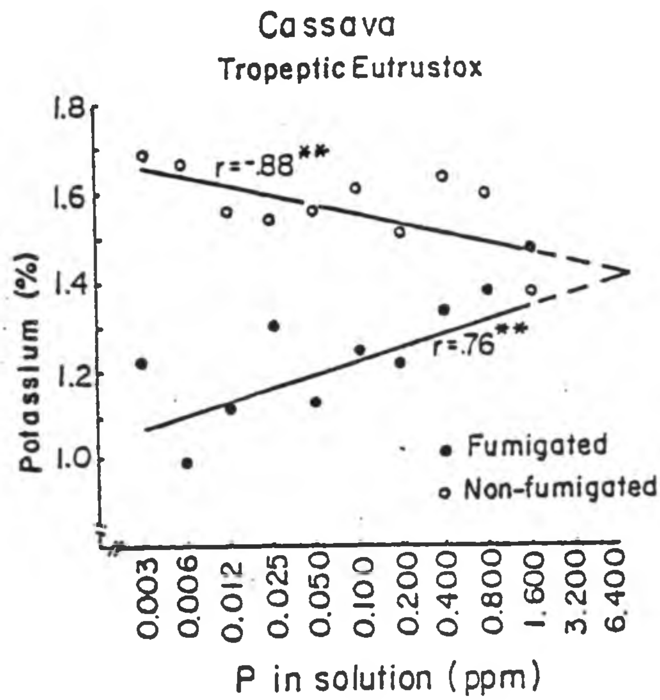


Figure 3.6 Potassium concentration in cassava leaf blades as affected by soil fumigation and soil P status

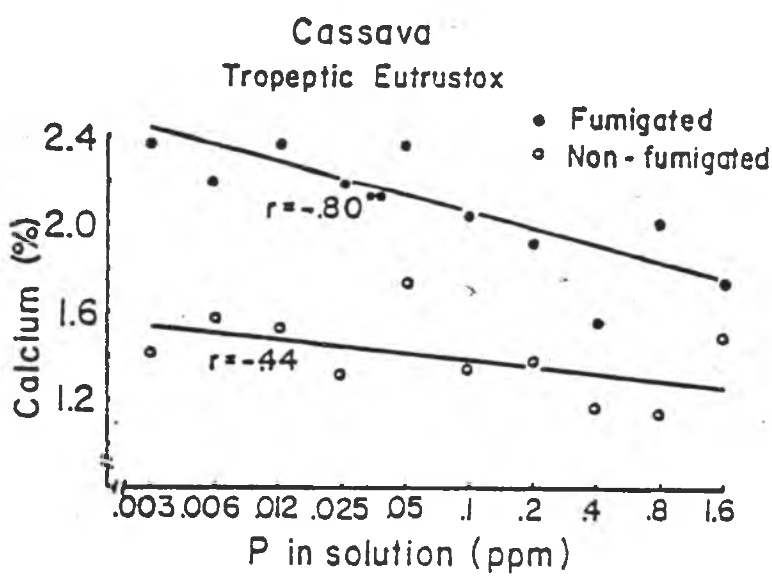


Figure 3.7 Calcium concentration in cassava leaf blades as affected by soil fumigation and soil P status

The reports in the litarature are not consistent on the effect of VA mycorrhizae on K uptake. Mosse (1957) and Powell (1974) report a positive influence of VA mycorrhizae on K uptake. Others found decreased K concentrations due to VA mycorrhizae (Gerdemann 1964, Kleinschmidt and Gerdemann 1972).

At low soil P levels, the calcium concentration in the leaves of plants grown on fumigated soil was 1.5 times those grown on non-fumigated soil (Fig. 3.7). The effect of fumigation on Ca concentration decreased with increasing P concentration in the soil. When the data are calculated as Ca uptake per leaf (data not presented), the differences between non-mycorrhizal and mycorrhizal plants disappear. Rhodes and Gerdemann (1978) have reported that Ca is not readily transported through the fungal hyphal lumen--an observation which may offer an explanation for the results reported here.

CONCLUSION

Cassava is able to extract sufficient nutrients for root production from some soils which by any standard are very infertile. One cultivar, which had a high yield potential, produced greatest root yields at 0.025 ppm soil P while five other cultivars did not respond to P fertilizers even when soil solution P was as low as 0.002 ppm. Our results demonstrate that cassava is able to do this by forming mycorrhizal associations. These mycorrhizae effectively increase absorption of P, K, S, and to a lesser extent Zn. Calcium absorption was not increased by mycorrhizal associations.

CHAPTER IV

THE UTILITY OF P SORPTION CURVES IN PREDICTING THE P REQUIREMENTS OF CASSAVA

INTRODUCTION

Studies in Hawaii show that cassava does not respond to P fertilization in the presence of VA mycorrhizae. However, the response to P is great when VA mycorrhizae are not present. Experimental results in the literature give varying results (Godfrey-Sam-Aggrey and Garber 1978, Vijayan and Aiyers 1969, Yong 1970, da Silva and Freire 1968). Experimental data are available but the results are generally site specific; that is, results obtained from one location cannot be transferred with confidence to other locations. One means for making experimental results more generally applicable is through the use of chemical soil tests. However, soil tests have limited value for predicting quantities of fertilizer required for specific crops grown under diverse field conditions. In the case of P fertilizer requirements, P sorption curves have been successfully used to estimate fertilizer P requirements of crops, and as the basis for transferring information about P fertilizer requirements from one location to another (Fox et al. 1974).

For this study, we used P sorption curves as a tool to combine information from 10 phosphate trials on cassava and estimated the requirements for P in the external (soil) solution. This external P requirement can be combined with P sorption curves to give a P fertilizer requirement.

MATERIALS AND METHODS

The procedures used for selecting field experimental data, for determining P sorption curves and for estimating P levels established in the field are as given in the section under General Methods.

Phosphorus Placement

The experiments at Hawaii and IITA, Nigeria had all the fertilizer broadcast and mixed into the top 15 cm of soil. The other experiments had the P fertilizer banded alongside of the cassava cuttings. With the use of P sorption curves we estimate the level of P in the soil solution. Obviously banding the P fertilizer gives a localized high P concentration while the remainder of the soil has not been affected. A physical theory on placement of fertilizers has been worked out by de Wit and summarized by Wijk (1966). The theory predicts that fertilizing the entire soil volume may not be the most efficient use of fertilizer when the quantity applied is less than that required for maximum uptake. In all but one of the experiments in this study the yield response was small, thus we assume that there is no significant advantage of placement. This is substantiated by results of Fox and Kang (1978) who observed no advantage to P placement over broadcasting at low P rates for maize. The results for cassava from Colombia may be influenced by P placement as the response is very sharp. However, for this comparative study we have assumed that there is no significant difference between banding and broadcasting the P fertilizer.

RESULTS AND DISCUSSION

P Status of Soils Investigated

The P sorption at a standard concentration (0.2 ppm P) in solution is presented in Figure 4.1. Values ranged from 23 μg P/g for the Quartzi-psamment (Thailand) to 650 μg P/g for the Gibbsihumox (Hawaii). P concentration in solution ranged from 0.002 ppm for the Gibbsihumox (Hawaii) to 0.012 ppm for the Oxic Paleustalf (IITA, Nigeria).

Yield Response to P Fertilization

In seven of the 10 experiments cassava showed little or no response to P. Results from Serdang (Malaysia), Thailand and Hawaii did not show responses to P fertilizer (Fig. 4.2). A slight response to P was obtained for the three experiments from Indonesia and for the one experiment from MARDI (Malaysia) (Figure 4.4). Variable responses were obtained for the experiments from Colombia and Nigeria (Figure 4.5).

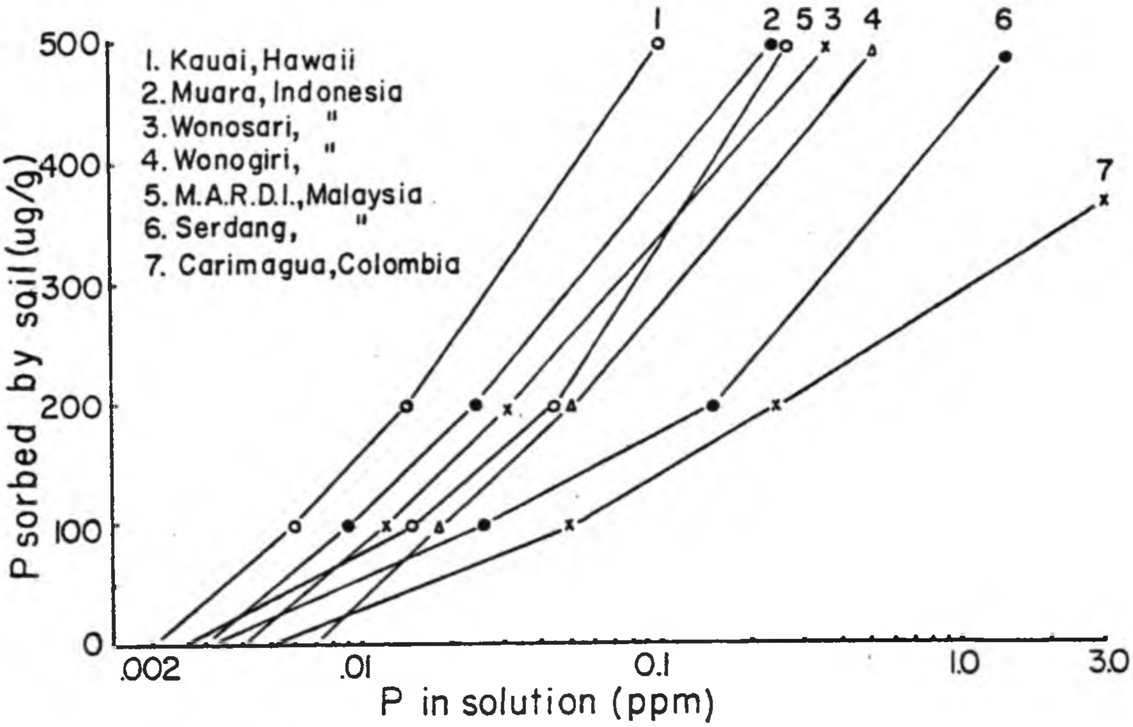
Hawaii Experiment

The results for this experiment are presented in the previous chapter under the section: cultivar experiment. The relative yield data is plotted in Figure 4.2.

Thailand Experiment

The Thailand experiment made use of field plots of Mr. Chote Sittibusaya, Field Crops Division, Department of Agriculture, Bangkhen. Particulars of the experiment were as follows. Five levels of N and four levels of P were planted in 1976 in the Cholburi region of southeast Thailand on a Sattaship Soil Series which is classified as a Quartzi-psamment. A representative soil sample was obtained for the location

(a)



(b)

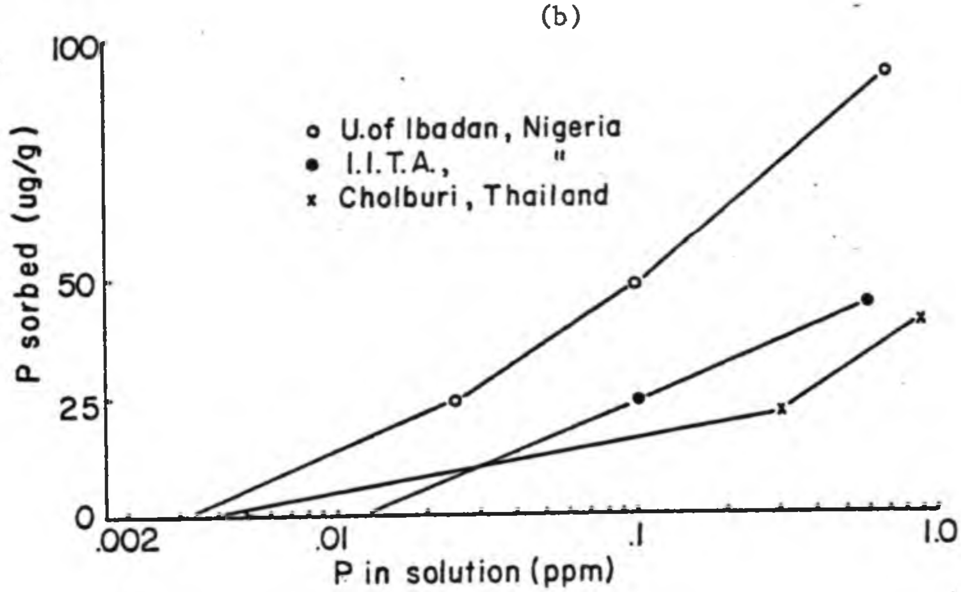


Figure 4.1 (a) P sorption curves for the soil from seven locations showing similar sorption characteristics.

(b) P sorption curves for the soil from three locations showing low P sorption characteristics in comparison with those in (a).

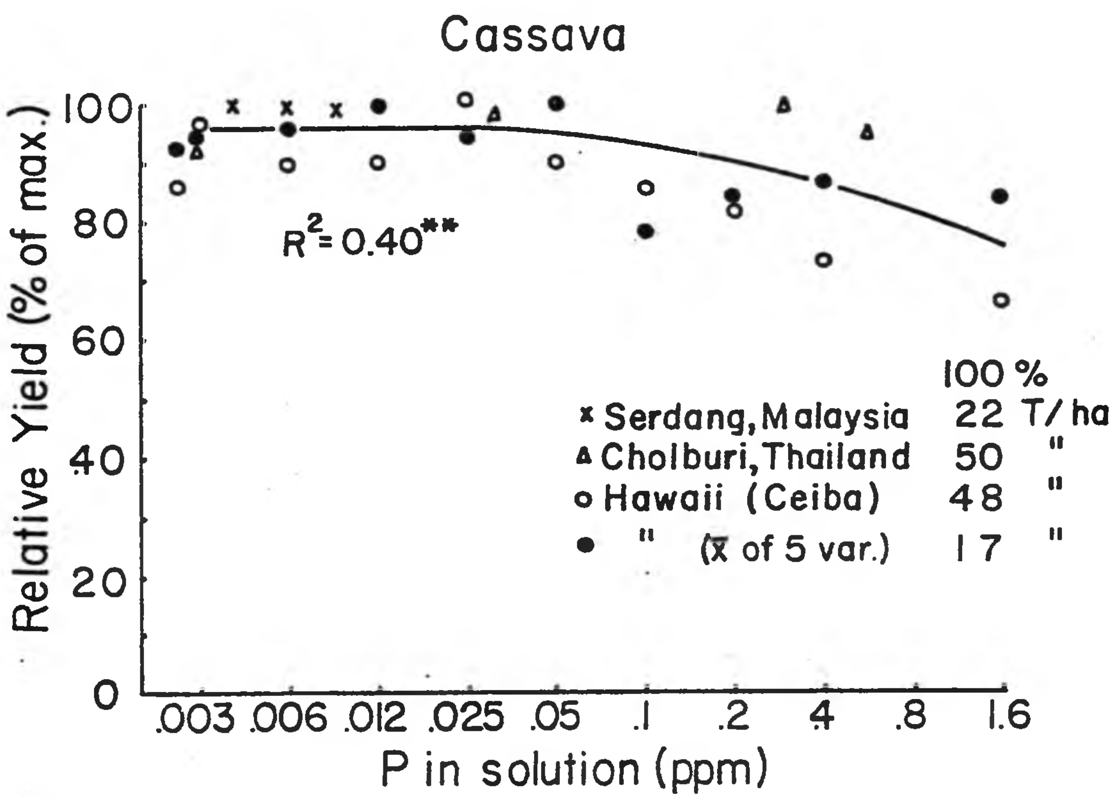


Figure 4.2 A composite yield response curve for cassava grown at three locations as a function of P concentration in solution

in 1978. A soil sample taken at the time of the experiment and analyzed in Thailand gave the following results: pH 5.1, Bray 2-P of 4 ppm. This sample was no longer available. The sample taken for the purpose of this study was taken in the vicinity of the plots in 1978 and analyzed in Hawaii. The pH was 4.8; Bray 2-P was 7.0 ppm. The soils were similar but not identical. A plot of yield as a function of estimated P in solution is presented in Figure 4.2. The response to P was not statistically significant. For the no P added plots the P in solution and extractable P levels are low, yet yields of 47 T/ha were obtained which is 93 percent of the maximum yield. This soil is classified as a Quartzi-psamment. As the name implies, the soil is predominantly quartz, thus having a low buffering capacity compared to the other soils in Figure 4.1. As a matter of speculation, it is probable that mycorrhizal associations played a major role in the P nutrition of the plant at the lowest level of P even though no VA mycorrhizae infection data nor internal P data are available.

Serdang Malaysia Experiment

Mr. Chan Seak Khen (Malaysian Agricultural Research Development Institute) established a P-K-Zn experiment in December 1977 on a Typic Tropudult at Serdang. Three rates of P were applied (9, 18 and 27 kg P/ha). A soil sample was obtained. Using the P sorption curve technique the estimated P in solution levels established were 0.004, 0.006 and 0.008 ppm (Figure 4.1). Plotting the yield as a function of P in solution gives a flat response curve (Figure 4.2). This suggests that 0.004 ppm P is adequate for optimum yields of cassava on this soil.

MARDI Malaysia Experiment

An NPK (3 x 3) factorial experiment was established on a Typic Troporthent in 1970. The P levels were 0, 15 and 30 kg P/ha, re-applied for each crop for 8 years. Data was obtained from Mr. Chan Seak Khen, coordinator of the cassava program at MARDI, for the fifth crop from each of the three P treatments. The predicted P levels using the P sorption curve technique were 0.0025, 0.005 and 0.007 ppm P in solution. Plotting yield versus the estimated P levels established (Fig. 4.3) suggests that maximum yields had not been attained. Maximum yield was estimated to be 43.3 T/ha using the Mitscherlich equation:

$$A = \frac{y_2^2 - y_1y_3}{2y_2 - y_1y_3}$$

Ninety-five percent of maximum yield is 41 T/ha which would be obtained at approximately 0.006 ppm P in solution. After five crops the no P added treatment produced 35 T/ha (81 percent of the estimated maximum yield). Thus the response to P is relatively small.

Indonesia Experiments

Three NPK (3 x 3) factorial experiments were established at Muara, West Java; Wonosari, Yogoyakarta Central Java; and Wonogiri, Central Java by Mr. Joses Wargino, Cassava Agronomist, Central Research Institute for Agriculture, Bogor. The P levels established were 0, 14 and 28 kg P/ha. Data was utilized from the plots which received 120 kg N/ha and the mean of two potassium levels (42 and 84 kg/ha). The P levels established were so low that the P concentrations in solution only increased by one ppb for each increment of P fertilizer applied (Table 4.1). Yield data

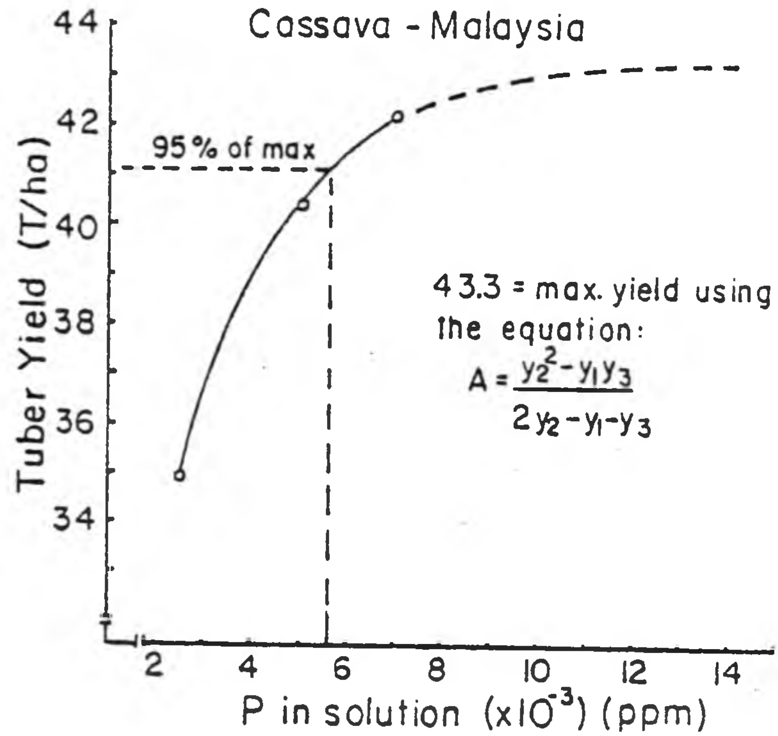


Figure 4.3 A yield response curve with an extrapolated maximum yield based on the Mitscherlich equation for the MARDI Malaysia experiment

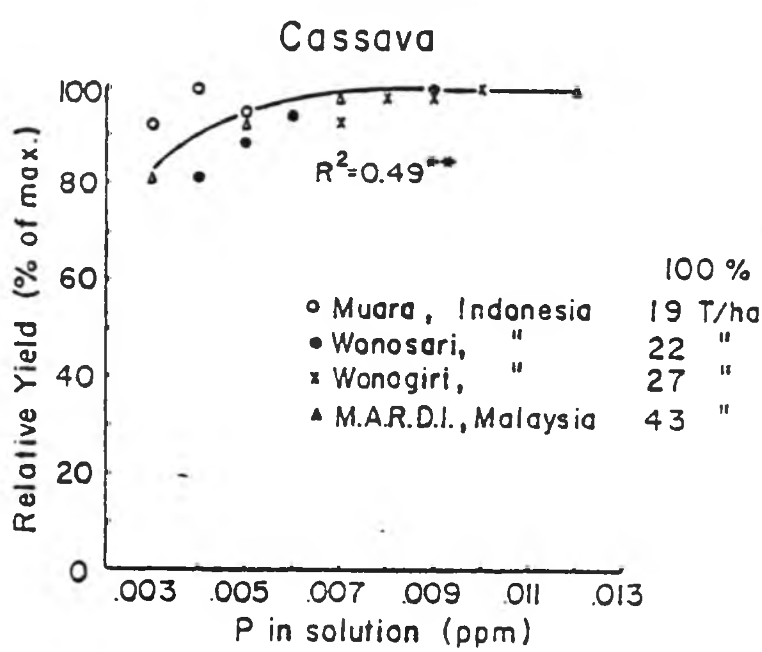


Figure 4.4 A composite yield response curve for cassava grown at four locations as a function of P concentration in solution

Table 4.1

Details Pertaining to the Ten Experiments Identified for Determining the P Requirements of Cassava

Location	Collaborating Scientist (Institution)	Soil Taxonomy subgroup	Soil pH	Extractable P levels (ppm) Bray-1	Bray-2	Olsen	NC	Organic matter %	Cultivar grown	N K rates applied kg/ha	P fertilizer rates (kg/ha) and estimated P in solution (ppm)	Fertilizer P to obtain 95% at max. yield	P in solution for 95% of max. yield	Relative yield of Po as % of max. yield
Carimagua Colombia	L. Hammond (CIAT)	Typic Haplustox	4.5	1.3	1.7	1.5	3.2	2.0	Llanera	100, 166	0 - .005, 22 - .007, 44 - .009, 175 - .04	42 kg/ha	.009	35
Hawaii USA	P. Van der Zaag (Univ. of Hawaii)	Typic Gibbsi-humox	5.4	0.8	1.1	3.0	0.6	5.0	Ceiba, Amarillo, Mameya, Nina, Seda, Pata de Paloma	100, 225	.002, .003, .006, .012, .025, .05, .1, .2, .4 and 1.6; levels re-established after each crop for past 7 years based on P sorption curves.	160 - Ceiba 75 - five varieties	.005 - Ceiba .003 - five varieties	86 - Ceiba 93 - five varieties
Muara Indonesia	J. Wargino (CRIA) Bogor	Aquic Tropudult	5.5	1.5	1.6	10.7	1.2	2.0	No. 547 (Gading)	120, x̄ of 50 and 100	0 - .003, 14 - .004, 28 - .005	14	.004	93
Wonosari Indonesia	J. Wargino (CRIA) Bogor	Typic Tropudalf	5.4	1.2	2.9	4.1	1.0	4.3	No. 547 (Gading)	120, x̄ of 50 and 100	0 - .004, 14 - .005, 28 - .006	28	.006	81
Wonogiri Indonesia	J. Wargino (CRIA) Bogor	Ustic Humitro-pepts	5.7	0.6	1.0	4.3	0.8	1.8	No. 547 (Gading)	120, x̄ of 50 and 100	0 - .007, 14 - .008, 28 - .009	14	.008	93
MARDI Malaysia	C. S. Khen (MARDI)	Typic Troporthent	4.1	7.4	32.0	4.9	10.0	3.1	Black Twig	50, 140	0 - .0025, 15 - .005, 30 - .007	80	.006	81
Serdang Malaysia	C. S. Khen (MARDI)	Typic Tropudult	4.6	4.2	9.8	3.7	3.0		Black Twig	50, x̄ of 25 and 75	9 - .004, 18 - .006, 27 - .008	< 20	.006	100
IITA Nigeria	B. T. Kang (IITA)	Oxic Paleustalf	6.4	7.4					Ishinuk-akiyan		0 - .012, 20 - .025, 35 - .05, 45 - .1, 65 - .2, 85 - .4	20	.03	75
Ibadan, Nigeria	G. Obigbesan (U. of Ibadan)	Oxic Paleustalf	6.2	3.2	4.0	2.4	2.1	1.6	60447	x̄ of, 50 30,60,90	0 - .003, 15 - .006, 30 - .012, 45 - .025	?	?	?
Cholburi Thailand	C. Sittibusaya (Dept. of Agric.)	Quartzi-psamment	4.8	2.4	7.0	2.3	2.0	0.7	local	128, 53	0 - .003, 23 - .03, 45 - .3, 68 - .6	6	.006	93

plotted as a function of estimated P in soil solution suggests that maximum yields were not obtained in the Wonosari and Wonogiri experiments. Applying the Mitscherlich equation used in the MARDI, Malaysia situation, the maximum estimated yields were 27 T/ha for the Wonosari location and 26 T/ha for the Wonogiri location. A yield approximating 95 percent of maximum was obtained at 0.006 and 0.008 ppm P in solution for the Wonosari and Wonogiri experiments. The no P added treatments had yields of 91 and 93 percent of the estimated maximum for the Wonosari and Wonogiri experiments. These responses are small considering the extremely low P levels presented (Table 4.1, Fig. 4.1). The Muara location did receive high enough P levels to get maximum yields. Interpreting the data against the other two locations, there appears to be an overall trend to maximum yields around 0.008 ppm P in solution (Fig. 4.4).

Colombia Experiment

Drs. Larry Hammond and R. H. Howeler, CIAT, compared six sources of P at the Carimagua farm of CIAT in Colombia. Yields, plotted as a function of the estimated P concentration in solution, are presented in Figure 4.5. The response to P was significant for the first two increments. The control treatment produced only 35 percent of maximum yield. This is a dramatic response to P as compared to data previously presented from Hawaii, Indonesia, Malaysia and Thailand--especially so since the level of P in the control plots was among the highest of all the locations investigated. Seventy kg P/ha (0.009 ppm) was required for 95 percent of maximum yield.

For the Colombia experiment plant P increased with increasing P fertilization (Fig. 4.6). The yield and internal P levels are highly

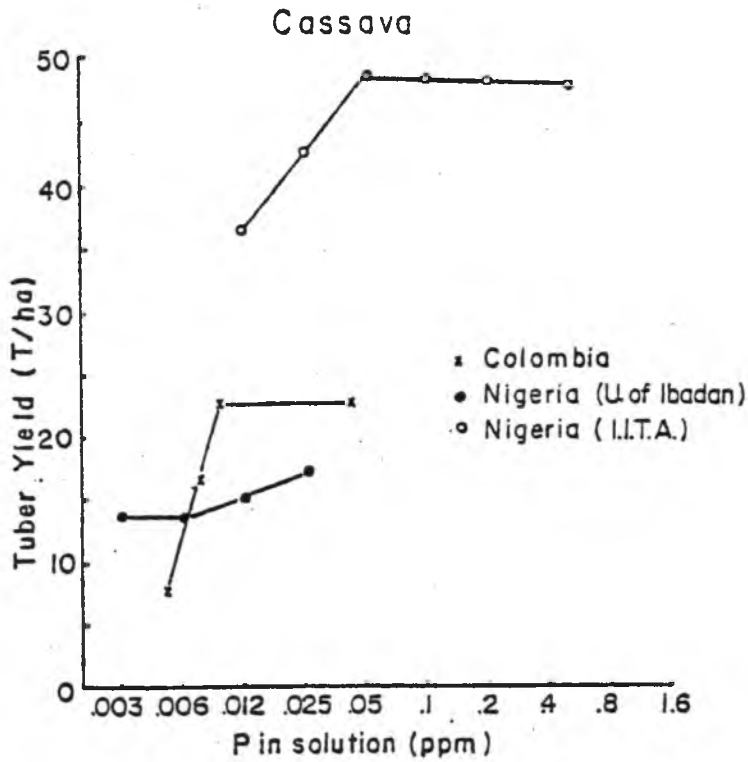


Figure 4.5 Yield response curves for cassava experiments grown in Colombia (Typic Haplustox) and at two locations in Nigeria (Oxic Paleustalfs)

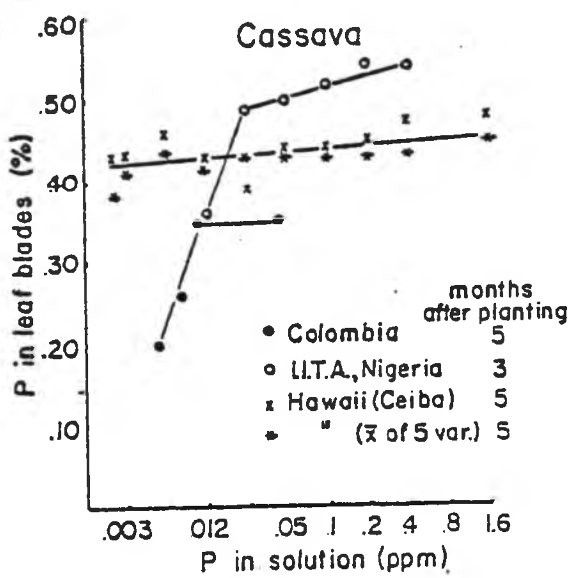


Figure 4.6 Comparative P concentration in the leaf blades of cassava as a function of estimated P in solution for three locations

correlated (Figs. 4.5 and 4.6).* It is interesting to compare the plant P of the Colombia and Hawaii experiments. In the Hawaii experiment the yield response and the internal P levels did not increase with increasing P in solution (Figs. 4.2 and 4.6). The plant P levels for the Colombia experiment are much lower, especially at the low P levels. This sharp response to P fertilization may indicate that the percent mycorrhizal infection was low. Data from Chapter III indicates that with no mycorrhizae present at low soil P levels, the percent P in the leaf blades is only 0.10 to 0.15 percent at 80 days after planting which is one third of the levels in the presence of mycorrhizae. The internal P level at 0.009 and 0.04 ppm P in solution is 0.35 percent, which is still lower than those obtained for the Hawaii experiment. This soil in the Llanos Orientales of Colombia is an acid infertile soil with high exchangeable aluminum (1.4 meq Al, total CEC is 1.8 meq).** This raises the possibility that mycorrhizae are sensitive to high levels of Al. This calls attention to the need for research on the physiological and nutritional requirements of mycorrhizae. For this experiment only 500 kg/ha of dolomitic lime was applied which raised the pH to 4.5. Ten kg $ZnSO_4$ were applied along with K_2SO_4 and KCl as potassium sources to improve the overall nutrient status of the experimental site.

IITA Nigeria Experiment

Dr. B. T. Kang fertilized soil with quantities of P designed to establish six levels of P in soil solution using the P sorption curve

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* CIAT Annual Report 1976.

** R. H. Howeler, personal communication.

technique of Fox and Kamprath (1970). The P fertilizer required to obtain these levels of P in solution are estimated using the P sorption curve (Fig. 4.1, Table 4.1). The lowest P level was 0.012 ppm P which is high in comparison to the other experiments presented in this study. However, a significant yield response to P fertilization was obtained (Fig. 4.5). At the lowest P level, the yield was 75 percent of maximum with 95 percent of maximum being around 0.03 ppm P. Internal P levels at 2.5 months after planting also responded to P fertilization (Fig. 4.6). The levels are higher than for the Hawaii experiment because the leaves were sampled at a younger age. The response to P fertilizer at levels where we obtained no P response in the previously discussed experiments is of interest. Dr. Kang did obtain mycorrhizal root infection data. At 2.5 months after planting the percent infection was approximately 35 percent and it decreased with increasing P fertilization. At harvest time (13 months) infection had increased to 55 percent. These infection levels are not high, yet one would expect they are sufficient to allow for more efficient P utilization from a soil which is relatively well supplied with P. The P sorption curve for this location indicates that this soil has a low buffering capacity in comparison to the other soils. This soil, an Oxic Paleustalf, is coarse in texture. Olsen and Watanabe (1963) showed that at equal moisture tensions the effective path length for diffusion is shorter for a clay soil than for a sandy soil. At a given moisture tension the clay soil will have a higher moisture content than the sandy soil and, therefore, a larger volume for diffusion. The slow rate of diffusion for this Oxic Paleustalf may be an explanation for why cassava had a high P requirement on this soil in comparison to the other locations. However, the Quartzi-psamment from Thailand had a very low external P requirement. Moisture conditions may have been optimal in the Thailand experiment. The IITA cassava data appears to be a discrepancy. Adjacent to it Fox and Kang (unpublished data) established a corn experiment with P as a variable in which the yield response curve was relatively flat in comparison to results obtained from Hawaii (Fox et al. 1974). The reason for the discrepancy is not known.

At our present state of knowledge, we cannot say much about VA myccorhizae strains and their efficiency in the uptake of P. It appears that the relative percentage of mycorrhizal root infection and the strains of VA mycorrhizae present are important for P nutrition. The fact that the internal P levels increased as the P in soil solution increased from 0.012 to 0.05 ppm P indicates that mycorrhizae were not adequately fulfilling their role in P uptake in comparison to the Hawaii results (Fig. 4.6).

Ibadan Nigeria Experiment

In 1976, Dr. G. O. Obigbesan, University of Ibadan, established a N x P experiment. Four levels of N and P were established. A blanket application of 50 kg K/ha was applied. Soil samples were obtained from all four replications and analyzed for P (Table 4.1, Fig. 4.1). The P sorption curve is similar to the one obtained from the IITA site except that the P status is lower.

There was no statistically significant response to either N or P (Fig. 4.5) and no N x P interaction (5 percent level). The coefficient of variation was 17 percent.

SUMMARY

Results from three experiments showed no response to P, while four experiments did show responses to the first increments of P with 95 percent of maximum being obtained at 0.005 ppm P.

Nine ppb or less was required for 95 percent of maximum yield in eight of the 10 experiments investigated (Table 4.1). The no P added plots in eight of the 10 experiments yielded more than 75 percent of maximum yield (Table 4.1). Thus the response to P is very small and if there is a marked response to P it would appear that a lack of, or ineffective strains of, VA mycorrhizae may be the reason for the sharp response to P in the Colombia and the IITA experiments.

Internal P levels gave a good indication of P nutrition of cassava and is apparently a good index of the mycorrhizal activity based on results from Colombia, IITA Nigeria and Hawaii.

It appears that P sorption curves can be used to transfer information about the P requirements of cassava. The P requirement for cassava is less than 0.008 ppm; there are variations in response to P up to that level. The variation can be attributed to VA mycorrhizal activity as well as to analytical difficulties with measuring P in solution less than 0.01 ppm.

CHAPTER V

THE PHOSPHORUS REQUIREMENTS OF YAMS (DIOSCOREA)

INTRODUCTION AND LITERATURE REVIEW

Yams provide a staple food for much of West Africa, Oceania, the Caribbean area, and parts of Asia. The three major species grown are *Dioscorea rotundata* (white yam); *D. alata* (greater yam) and *D. esculenta* (lesser yam). In West Africa, where *D. rotundata* predominates, yams are grown under shifting cultivation, primarily during the first year after burning secondary forest. The remaining tree trunks act as a natural support for the vines. Such traditional agriculture usually does not include commercial fertilizer. However in West Africa as well as in parts of Asia, Oceania and in the Caribbean area, all three species of yams are grown with some fertilization around village homes.

The nutritional requirements of yams have not been firmly established. Some research has been devoted to P nutrition. Brown (1931) in a general review of yam cultivation obtained yield responses to P fertilization in the West Indies. Koli (1973) performed three field experiments in the savanna of northern Ghana to determine the fertilizer requirements of *D. rotundata*. The initial P levels in the soil ranged from 10-15 ppm using the Bray 1 extractant. No significant yield responses to P fertilization were observed. Nitrogen fertilization produced a positive yield response but potassium fertilization did not. Irving (1956) coordinated numerous yam fertilizer experiments in Eastern Nigeria. With few exceptions he observed no response to P.

The pivotal role of vesicular-arbuscular (VA) mycorrhizae in the P nutrition of cultivated plants has not been widely appreciated until recent years. These mycorrhizae are particularly beneficial for crop growth in P deficient soils but they may enhance the uptake of other nutrients too (Mosse 1973). The hyphae absorb and translocate P into the root from a larger soil volume than is normally exploited by non-mycorrhizal roots. Sanders (unpublished data) observed that on soils in Nigeria *D. rotundata* roots are heavily infected with mycorrhizae. No doubt the yam plant utilizes P efficiently at low levels of soil P because of these mycorrhizal associations.

This chapter deals with the external (soil solution) P concentration and internal (plant tissue) P percentages of the three important yam species in relation to root yield. The presence of VA mycorrhizae on yam roots grown at various levels of P was verified.

MATERIALS AND METHODS

Two general approaches were used in doing this study:

1. Field experiments were performed in Hawaii with P treatments based on laboratory analysis of soil samples representing the experimental site.
2. Existing data from previously performed field experiments were obtained from Ghana and Nigeria and were compared. These field data consisted of yield in relation to quantities of P fertilizer added. The criteria used for selecting these locations were: (a) the replication was adequate, (b) the cultural practices were adequate and (c) the yields were acceptable for those locations.

Hawaii Field Experiments

Phosphorus solubility gradients were established across blocks of land 16 meters long (Fox 1973). The gradients were established by subdividing the blocks into 16 steps, each being one meter in width. Phosphorus was applied to each strip to provide P in soil solution ranging from 0.005 to 1.0 ppm. The quantities of fertilizer required to establish these concentrations were determined using the P sorption curve technique of Fox and Kamprath (1970). Amounts of P, broadcast as Treble Super Phosphate, ranged from 0 to 1300 kg P/ha. The stepwise gradient produced by the one-meter increments was converted into a smooth gradient by rotovating the surface soil (0-15 cm) in both directions. The treatments were replicated four times.

Planting material was obtained from Dr. F. Martin in Puerto Rico. Three varieties of *D. esculenta* (S.E.A. 32, 97 and 273) and two varieties of *D. alata* (S.E.A. 25 and 241) were planted at a 1 meter x 1 meter spacing. The *D. esculenta* planting material was tubers. For *D. alata* only single tubers were obtained. These were planted and from the vegetative growth produced, stem cuttings were made which included one or two leaves, petioles and 4 cm of the main vine. These were treated with a growth hormone (indole 3 butyric acid 0.1 percent) and placed in trays filled with a vermiculite-perlite mixture in a mist chamber. More than 80 percent of the cuttings produced roots and shoots within 5 weeks, after which time they were transplanted to pots containing a soil-perlite-vermiculite mixture for two weeks before being transplanted across the P gradient in the field. Nitrogen was added as ammonium sulfate and urea in a split application totaling 100 kg N/ha. Irrigation was by furrows between rows. Nylon netting two meters in height strung between steel posts were provided for vine support to increase the efficiency of light interception.

At four months of age leaf samples of four varieties were taken at nine locations across the P gradient. Ten recently fully matured leaf blades and petioles were taken. P was analyzed after the samples were digested with 2:1 nitric-perchloric acid (Blancher et al. 1965). Other mineral nutrient elements were analyzed by X-ray fluorescence. At harvest (8 months after planting) root samples were taken to determine the relative amounts of mycorrhizal infection using the procedure of Phillips and Hayman (1970). Tubers were also sampled and analyzed for the major elements by X-ray fluorescence.

Following this experiment the plots were re-fertilized to re-establish the original gradient of P across each block. This second fertilizer application required Treble Super Phosphate in the amount of 0 to 250 kg P/ha. Tuber seed pieces for the two varieties of *D. alata* (S.E.A. 25 and 241), obtained from the initial experiment, were planted in two replications in April 1978 at a spacing of 1 meter x 0.67 meter. The purpose of this experiment was to determine whether or not the response to P by yams would be different for plants grown from stem cuttings and from tuber seed pieces. Cultural practices, plant sampling and analytical procedures were similar to the initial experiment except that leaf samples were taken at 5 months of age and the experiment was harvested at 7 months after planting.

Ghana Experiments

Results of three experiments were obtained from the forest-savanna transitional zone of Ghana at Ejura, Atebubu and Wenchi respectively (P. Kwakye, Soil Research Institute, Kumasi, Ghana, unpublished data). In all the experiments the species D. rotundata (variety-Dentenpruka) was grown. Yams were spaced 1.25 m x 1.25 m; were staked on poles and the treatments were replicated four times. The soils at all three locations are classified as Typic Paleustults.

All the fertilizer was applied in a groove about 20 cm from the base of each plant and about 5 cm deep. We are assuming no difference between broadcast and placed fertilizer applications because the initial P levels were medium to high. The results of Fox and Kang (1978) indicate that there were no marked differences between band applied and complete incorporation of P for maize in Nigeria.

At Ejura a N P K 3^3 factorial experiment was established in 1973. The P rates were 0, 15 and 30 kg/ha. According to the P sorption curve (Fig. 5.1) the indicated values of P in solution (assuming complete incorporation of P into the surface soil) would have been 0.018, 0.08 and 0.35 ppm P (Table 5.1).

The Atebubu and Wenchi experiments were planted in April 1976 to study the relative effectiveness of phosphate sources. For the purposes of this study, data were utilized from the combined results of the Treble Super Phosphate and Single Super Phosphate treatments. Details related to the P rates, estimated P levels and other fertilizer information are given in Table 5.1.

In all cases the yams were harvested 7 to 8 months after planting. Only data on tuber yield were available from these experiments.

Nigeria Experiment

Data were utilized from a N x P factorial experiment which was performed at Eruwa in the savanna region of Nigeria (G. O. Obigbesan, Department of Agronomy, University of Ibadan, Ibadan, Nigeria, unpublished data). The experiment utilized four levels of N (0, 30, 60 and 90 kg/ha) and three levels of P (0, 30 and 60 kg/ha). According to the P sorption curve constructed from data generated in Hawaii, the estimated P levels in soil solution were 0.005, 0.07 and 0.6 ppm P. The experiment was planted on March 15, 1977 and harvested on January 6, 1978 with *D. rotundata* (variety-Aro) at a spacing of 0.9 m x 0.9 m. The fertilizer was placed around each plant, the plants were staked and harvested after 9 months. Only data on tuber yield were available from this experiment.

RESULTS AND DISCUSSION

Comparative P Sorption of Soils from Experimental Sites

The soils on which the *D. rotundata* experiments were sited are representative of some important soils in West Africa. Standard P sorption (at 0.2 ppm P in solution) is low for these soils as defined by Juo and Fox (1978). This predicts that small amounts of fertilizer P will increase the P in solution more than is typical for much of the tropics but since these soils are poorly buffered they can be quickly depleted of their P, perhaps with only one or two crops. These soils are in sharp contrast to the Hawaii soil which has a high P sorption capacity (Fig. 5.1). Several methods agree that the P status of the Ghana soils is high relative to the soils from Nigeria and Hawaii (Table 5.1).

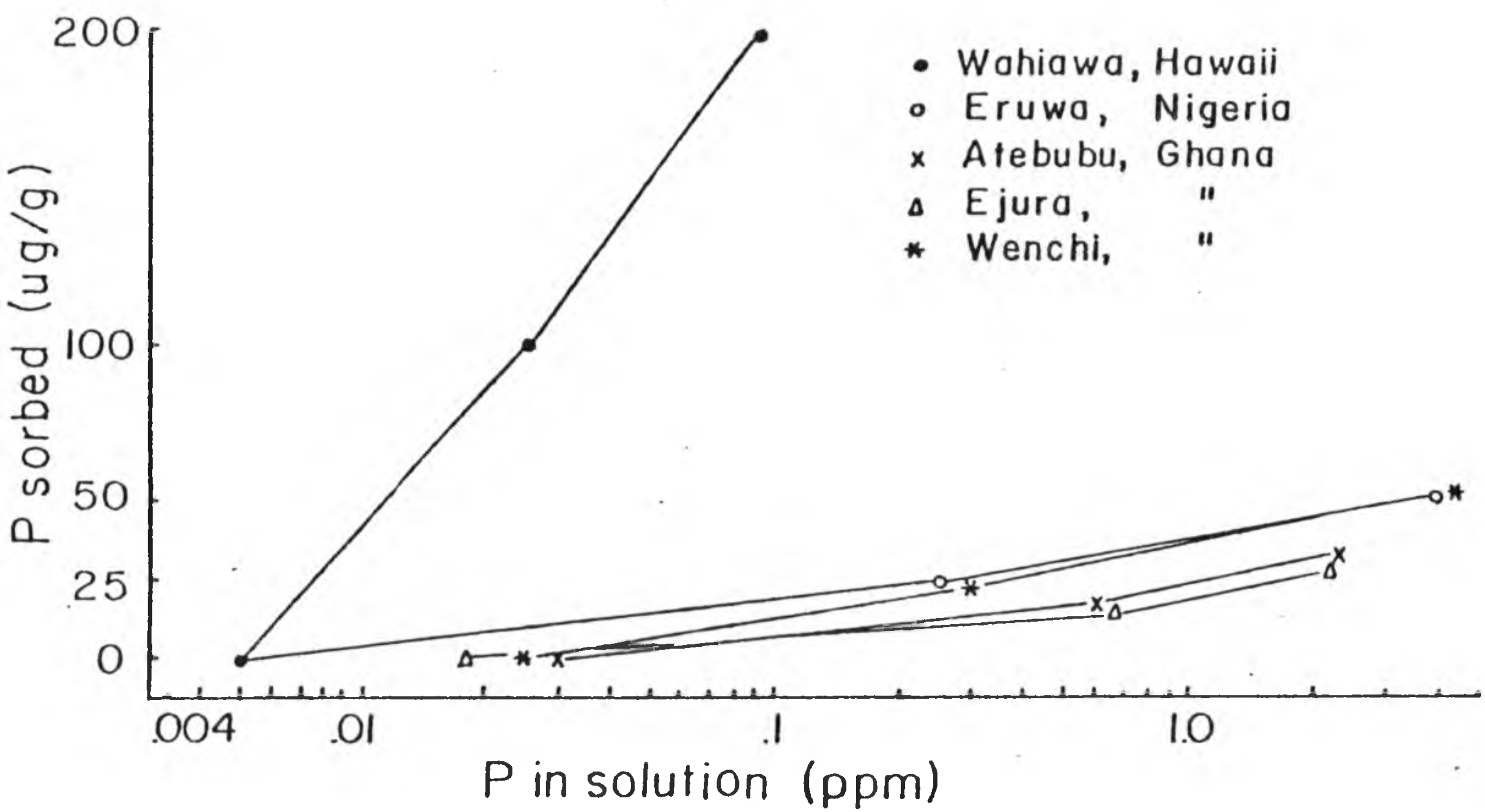

Figure 5.1 P sorption curves for the soils from five locations showing a diversity of sorption characteristics and variable initial levels of P in solution

Table 5.1

Details of the Phosphorus and Other Nutrient Status for the Five Experiments Where Yams Were Grown

	Location				
	Ghana			Nigeria	Hawaii
	Atebubu	Ejura	Wenchi	Eruwa	Wahiawa
	Typic Paleustult	Typic Paleustult	Typic Paleustult	Oxic Paleustalf	Tropeptic Eutrustox
pH	6.5	6.5	6.5	5.8	5.8
	— Extractable P (ppm) —				
Bray 1 0.025 N HCl + 0.03 N NH_4F	19.1	13.1	15.8	5.4	6.5
Olsen 0.5 M Ha HCO_3	11.7	3.9	7.0	5.8	24.6
Double Acid 0.05 N HCl + 0.025 N H_2SO_4	14.5	7.9	12.1	5.6	5.2
P sorbed at 0.2 ppm in solution (μg/g)	12	12	18	20	320
Initial P in solution (ppm)	.03	.018	.025	.005	.005
P rates kg/ha	0,26,52	0,15,30	0,26,52	0,30,60	0 - 1300
P sources	SSP,* TSP**	SSP	SSP, TSP	TSP	TSP
N rates (kg/ha)	45	$\bar{x}$+ 40, 80	45	$\bar{x}$ 30,60,80	50
K rates (kg/ha)	37	$\bar{x}$ 33, 66	37	60	.75 meq/ 100 g

* SSP = Single Super Phosphate

** TSP = Treble Super Phosphate

\+ Mean of rates presented was used in determining the yield response to P.

P Response by Dioscorea Alata (Hawaii)

Yields of yams grown from tuber seed were substantially higher than those from stem cuttings (Fig. 5.2). This increase in yield can probably be attributed to more vigorous vine development and increased yield potential from seed pieces than from cuttings. Yields were influenced by P fertilization. Variety S.E.A. 25 (seed pieces) responded to the first few increments of P with maximum yields of 39 T/ha attained at approximately 0.01 ppm P in solution. Variety S.E.A. 25 (stem cuttings) did not respond to P fertilization, however the yields were only 6 to 9 T/ha. Variety S.E.A. 241 was much more vigorous with yields from stem cuttings as great as 50 T/ha. This variety may respond to the first increments of P. However, yields of S.E.A. 241 (seed pieces) were as much as 87 T/ha. Such a high yield was accompanied by a substantial response to P fertilization. Maximum yields were obtained at approximately 0.02 ppm P in solution. Variety S.E.A. 241 yields varied considerably because, with the continuous function design, only one meter increments of row were available for each sample. Running means were used to smooth out the data, but even so the data for variety S.E.A. 241 are variable.

The internal P concentrations in *D. alata* (Table 5.2) were not influenced by P fertilization. The internal P levels in the leaf blades for S.E.A. 25 and 241 were similar to those reported by Obigbesan and Agboola (1978) for *D. alata* in Nigeria. An interesting aspect of this data is that the P concentration in the leaves of the plants grown from seed pieces was 50 percent greater than plants grown from cuttings. Increased P in the plant associated with seed-piece planting material

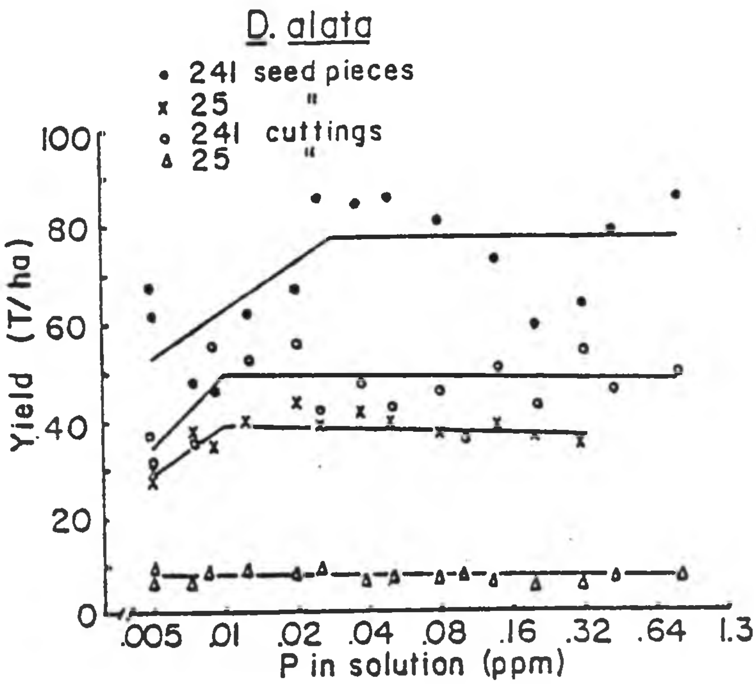

Figure 5.2 The yield response curves for two varieties of D. alata grown in Hawaii as a function of P concentration in solution

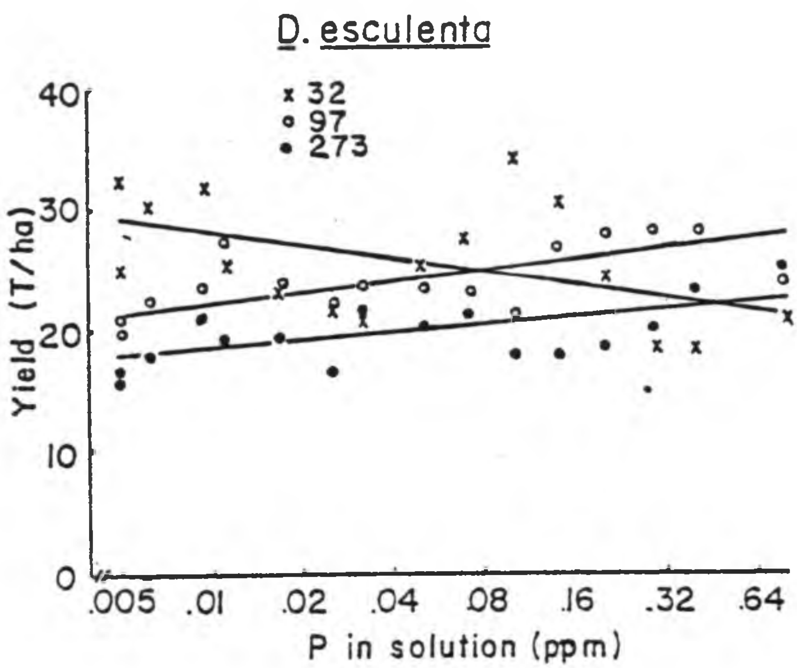

Figure 5.3 The yield response curves for three varieties of D. esculenta grown in Hawaii as a function of P concentration in solution. The correlation coefficients for the three varieties were as follows: 32, r = 0.47; 97, r = 0.63**; and for 273, r = 0.53*.

Table 5.2

Phosphorus Content in the First Fully Matured Leaves (Petiole and Blade) of Yams on an Oxisol in Hawaii

P Treatment (ppm P in soln.)	Months after Planting 4					5	
	Variety						
	Seed pieces			Stem cuttings		Seed pieces	
	32	97	273	241	25	241	25
0.005	.24	.29	.29	.18	.21	.33	.33
0.005	.29	.36	.30	.21	.21	.33	.34
0.01	.32	.36	.35	.20	.21	.34	.29
0.02	.29	.39	.38	.22	.20	-	-
0.04	.32	.36	.39	.24	.18	.32	.32
0.08	.34	.36	.36	.22	.24	-	-
0.16	.34	.37	.45	.20	.19	.30	.33
0.32	.34	.35	.43	.26	.18	-	-
1.00	.33	.37	.37	.19	.19	.31	.32

Table 5.3

Mycorrhizal Infection (Percent of Primary Cortex) in Young Roots of Yams (*D. esculenta* varieties S.E.A. 32, 97, 273 and *D. alata* varieties S.E.A. 241, 25) Grown in Hawaii, as influenced by P fertilization

Estimated P level established (ppm)	Variety					
	Seed pieces			Stem cuttings	Seed pieces	
	32	97	275	241	241	25
0.005	80	50	40	60	60	40
0.007	80	40	40	50	60	30
0.012	-	-	-	30	30	30
0.25	60	50	40	40	30	20
0.05	30	10	30	-	30	20
0.1	-	-	-	40	20	20
0.2	20	20	30	30	30	20
0.4	-	-	-	10	30	10
0.8	30	10	20	-	20	20

corresponded with increased tuber yields (Fig. 5.2). There were no visual symptoms that the plants grown from cuttings were deficient in P. Furthermore, for variety S.E.A. 241 the VA mycorrhizal infection was similar for plants developed from stem cuttings and seed pieces (Table 5.3). These results suggest that something very important in the P economy of the plant is taking place, perhaps associated with a more adequate supply of energy material from the seed piece early in plant development. This further suggests a vigorously proliferating root system with an earlier, well-developed, mycorrhizal association when plants are developed from seed pieces.

These data indicate a relationship between crop yield potential and external P requirements. There also is evidence of this kind of relationship in studies of Fox and Kang (1978). They observed that the external P requirements for maize increased when yield potential was increased by reason of improved light intensity.

P Response of Dioscorea Esculenta (Hawaii)

The vegetative growth of the three *D. esculenta* varieties was vigorous. At 8 months of age the crop was harvested even though the vines were still green. The yields were not greatly affected by P fertilization; two varieties produced a positive trend and one variety a negative trend. Linear regression lines giving significant correlations in two cases best described the yield data (Fig. 5.3). The relative yields at low P levels correspond to the relative VA mycorrhizal infection for these three varieties (Table 5.3). Variety S.E.A. 32 was 80 percent infected at the lowest P level whereas varieties S.E.A. 97 and 273 were only 40-50 percent infected. This may provide an explanation why S.E.A. 97 and 273 responded positively to the applied P while S.E.A. did not respond. In all cases the percentage of mycorrhizal infection decreased with increasing P fertilization (Table 5.3).

The internal P concentrations (soil) increased with P fertilization up to 0.16 ppm P in solution (Fig. 5.5, Table 5.2). Even though P concentration in the plant increased, there was no yield response to P (Figure 5.3). Therefore the internal P level was not a good indicator of whether or not there was a yield response to P fertilization. The internal P levels were in the same range as for *D. alata* varieties grown from seed pieces (Table 5.2).

P Response by Dioscorea Rotundata (Ghana and Nigeria)

The yield response to P was not significant in any of the four experiments (Figure 5.4). The results indicate that *D. rotundata* efficiently utilizes P even at low levels (0.005 ppm P in solution); however, the yields obtained were relatively low. Only at one location were the yields sufficiently high enough to even expect a yield response if *D. rotundata* behaves similar to *D. alata* in Hawaii (Figure 5.2).

Internal Concentrations of Other Nutrients in D. alata and D. esculenta

Nutrient levels in the plants did not vary much between varieties and species except for high Mn concentration in variety S.E.A. 241 (stem cuttings) (Table 5.4). A comparison of these results with those of Gaztambide and Cibes (1975) (a greenhouse study using sand culture to which a nutrient solution was added) reveals some discrepancies and similarities. Concentrations of N, Fe and Mn were similar whereas K was four fold higher and Ca, Mg and S were lower in the study reported

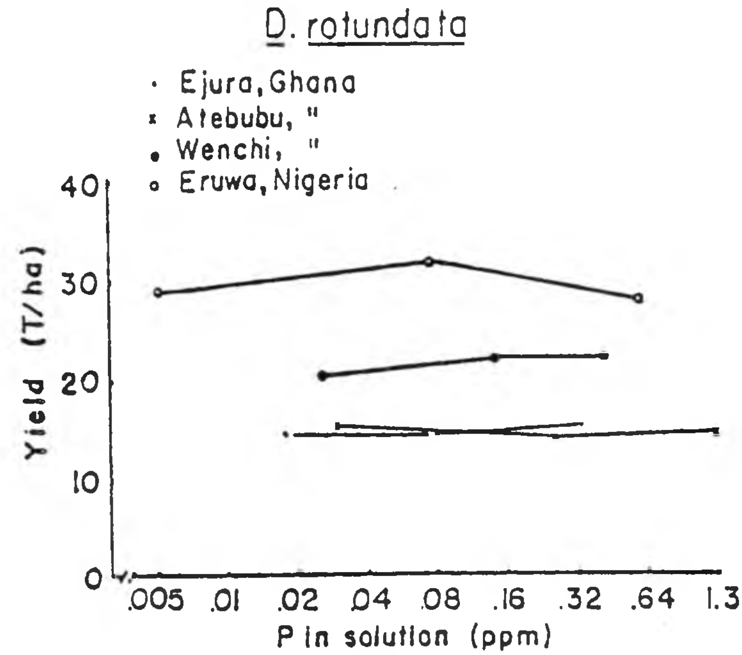

Figure 5.4 The yield response curves for D. rotundata as a function of estimated P concentration in solution for three locations in Ghana and for one location in Nigeria

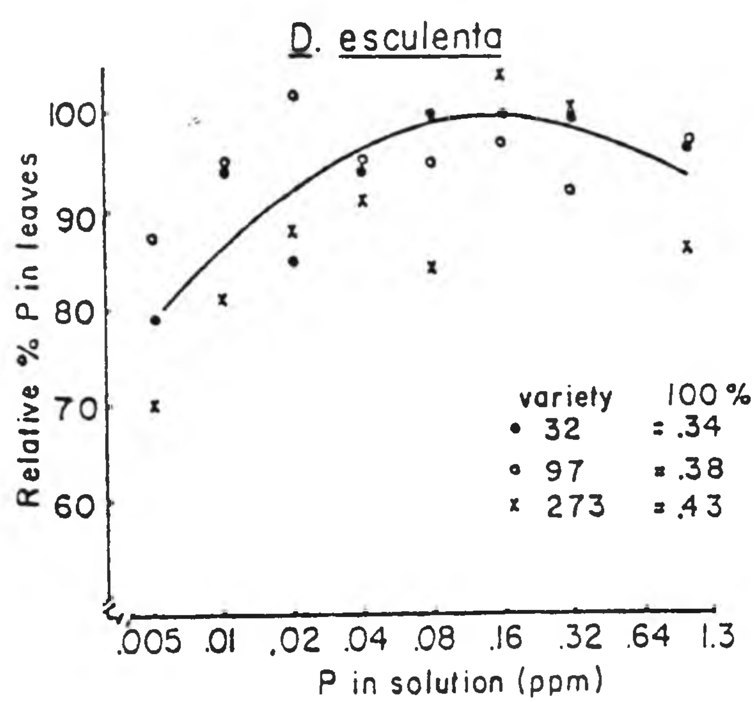

Figure 5.5 The relative concentration of P in the tissue of three varieties of D. esculenta as a function of P concentration in solution

Table 5.4

Nutrient Levels in the Leaves (Petioles and Blades of the First Fully Matured Leaves) of Three Varieties of D. esculenta and Two Varieties of D. alata for the 0.012 ppm P in Solution Treatment at 4 Months of Age for Varieties S.E.A. 32, 97, 273, 241 (Stem Cuttings) and at 5 Months of Age for Varieties S.E.A. 241 and 25 (seed pieces)

Variety	N	K	Ca	Mg	S	Na	Cl	Mn	Fe	Cu	Zn
				%					ppm		
D. esculenta											
32	2.3	2.3	1.3	.23	.13	.10	.22	469	185	12	32
97	2.7	2.6	1.1	.23	.15	.10	.22	306	188	16	46
273	2.8	3.1	1.1	.27	.14	.10	.19	370	188	18	43
D. alata											
241 (stem cuttings)	2.9	3.1	1.8	.33	.17	.10	.55	1243	152	16	42
241 (seed pieces)	2.1	3.4	1.3	.19	.16	.07	.88	457	256	26	38
25 (seed pieces)	2.2	3.1	1.1	.20	.16	.08	.79	251	163	28	37

Table 5.5

Mineral Nutrient Levels in Yam Tubers of Three Varieties of *D. esculenta* (S.A.E. 32, 97, 273) and Two Varieties of *D. alata* (S.E.A. 25 and 241) for the 0.02 ppm P Treatment

Variety	N	P	K	Ca	Mg	S
	percent					
32	.90	.14	1.0	.09	.09	.05
97	.88	.17	.9	.07	.10	.05
273	1.16	.16	1.5	.10	.10	.06
25 (stem cuttings)	1.21	.17	1.6	.05	.06	.05
241 (stem cuttings)	.86	.15	1.6	.05	.06	.02
25 (seed pieces)	.92	.16	1.3	.09	.02	.04
241 (seed pieces)	1.14	.20	1.7	.11	.03	.07

here. For D. alata the levels of N, K, Ca and Mg were similar to those reported by Obigbesan and Agboola (1978).

Tubers were analyzed for some of the most abundant nutrients (Table 5.5). For D. alata the levels of N, P, K, Ca and Mg were in the same range as those obtained by Obigbesan and Agboola (1978). In all cases, except for Ca, concentrations were higher for yams than for cassava (Chapter III). Phosphorus content of yam tubers ranged from 0.14 to 0.17 percent which is two times those found in cassava, higher than in sweet potatoes, similar to potatoes, and lower than in taro (Table 5.5; Chapters I, II, III, VI).

SUMMARY

Yams have external P requirements ranging from 0.005 to 0.02 ppm P in solution. D. alata had the highest P requirement but also gave the highest yields. D. esculenta and D. rotundata which produced lower yields did not respond to P fertilization. There appears to be a relationship between yield potential and the external P requirement of yams.

Internal P concentration was not a good indicator of whether or not there would be a yield response to P fertilization for D. alata and D. esculenta.

All three species of yams efficiently utilize P at low concentrations in the soil solution. It seems reasonable to suppose that yams depend on an effective mycorrhizal association to meet their P requirement.

CHAPTER VI

THE PHOSPHORUS REQUIREMENTS OF TARO

(COLOCASIA ESCULENTA)

INTRODUCTION AND LITERATURE REVIEW

Taro, dasheen, kalo, dalo, keladi, arvi, gabi, eddoe, curcas and "old" cocoyam are all forms of a plant originally described as *Arum esculenta* L., but now referred to as *Colocasia esculenta* (L.) Schott (Coursey 1968, Plucknett 1978). The name in Hawaii is taro. Originating in Southeast Asia, *Colocasia* was spread by prehistoric man through India and the Pacific (Coursey 1968). *Colocasia* is now cultivated in virtually all tropical and subtropical countries. Approximately 760,000 hectares produce 4.4 million tons of corms annually (FAO Yearbook 1974).

Although *Colocasia* is an adaptable crop, it needs a fertile soil for maximum growth. When grown under less than ideal conditions it responds to fertilization (Hodnett 1958, Plucknett and de la Pena 1971). Taro has responded substantially to P fertilization both under lowland conditions and upland conditions in Hawaii (Plucknett and de la Pena 1971). In their experiments P rates ranged from 0 to 1120 kg/ha with optimum yields being obtained around 200-500 kg P/ha.

Fox and de la Pena (unpublished data) have attempted to relate taro production to concentrations of P in soil solutions. Plots were fertilized with phosphate as prescribed by a P sorption curve developed for the experimental site. There were 10 levels of P. Soil solution was extracted wtih a ceramic filter candle taking care that the solution was not exposed to atmospheric oxygen. There was no significant yield response by the taro to P. The lowest P level determined was 0.02 ppm P in solution. Near maximum yield coincided with an internal P concentration of 0.41 percent (Appendix Table 11).

With the exception of the study by Fox and de la Pena (unpublished data) no soil P test data has been presented. Results from such experiments have limited value because soil variability may be such that edaphic conditions which apply to the experiment may not be repeated in an adjacent field, much less in another country. A soil P test is needed which correlates soil P status with taro yield. Such a test would make it possible to utilize experimental data much more widely. It is unlikely that a conventional test for phosphorus "availability" can be used to accommodate the taro crop, especially taro grown on flooded soils.

This study focused on upland taro. The external P requirements of three taro varieties have been determined with reference to P in soil solution as predicted by P sorption curves. These values have been compared with _in situ_ measurement of the external P requirement of lowland taro.

MATERIALS AND METHODS

The experiment was sited on the island of Kauai on a Typic Gibbsihumox under upland conditions. Plots were used which had 10 levels of P established in 1971 in an augmented block design. The plots were cropped repeatedly and refertilized before each crop to establish P levels in solution of 0.002, 0.003, 0.006, 0.012, 0.025, 0.05, 0.1, 0.2, 0.4 and 1.6 ppm. The P fertilizer requirements to establish these levels of P in solution were obtained using the P sorption curve technique. The concentrations found prior to this experiment and the rates required to obtain the desired levels are given in Table 6.1.

The P plots were split with the pH adjusted on one half of each plot with $CaSiO_3$ and on the other half with $CaCO_3$. The pH values were re-adjusted to 6.0 prior to the taro experiment.

Liming materials, phosphorus, 100 kg K/ha as muriate of potash and 50 kg N/ha each of ammonium sulphate and urea were broadcast applied then rotovated into the surface 15 cm of soil before planting taro.

Three varieties of _C. esculenta_ were planted in subplots: Lehua, the most common variety in Hawaii; Bun Long, a new chipping variety; and dasheen, locally called "araimo" (6 month variety). Three rows each of Lehua and Bun Long and two rows of dasheen at a spacing of 60 x 60 cm were planted in January 1978.

Leaf blades were sampled 3 months after planting, using as sample material the most recently fully expanded leaf. Root samples were also taken to determine the amount of vesicular arbuscular mycorrhizal infection in the root cortex. At this time another 100 kg/ha of N and K were applied as urea and muriate of potash, respectively.

The dasheen matured early and was harvested during late September 1978. The varieties Lehua and Bun Long were harvested in late October 1978. Corm and root samples of the Lehua and Bun Long varieties were analyzed for nutrients and examined for VA mycorrhizae, respectively. The leaf samples and corms were analyzed for nturients (except P) using X-ray fluorescence Quantometer. The P content of corms was determined in a 2:1 nitric perchloric acid digest (Blanchar 1965). The VA

Table 6.1

Fertilizer P Requirements to Re-establish the Desired P Concentrations for the Taro Experiment on Kauai (Typic Gibbsihumox)

Phosphorus Treatment	Repli-cation	P Concentration Found (ppm)	P Level Desired	P Required (μg/g)	P Required (kg TSP/plot)
1	2	.0038	----	0	0
2	3	.0038	.003	0	0
3	1	.0025	.006	110	6.36
3	2	.0025	.006	110	6.36
4	1	.0038	.012	120	6.94
4	2	.0025	.012	140	8.09
4	3	.0050	.012	100	5.78
5	1	.0025	.025	175	10.12
5	2	.0050	.025	125	7.23
5	3	.0050	.025	145	8.38
6	1	.0063	.05	210	12.14
6	2	.0075	.05	185	10.69
6	3	.0090	.05	160	9.25
7	1	.0160	.10	190	10.98
7	2	.0150	.10	205	11.85
7	3	.0150	.10	200	11.56
8	1	.0380	.20	220	12.72
8	2	.0390	.20	215	12.42
9	2	.0590	.40	290	16.76
10	3	.4100	1.6	300	17.34

mycorrhizal infection was determined by the procedure of Phillips and Hayman (1970).

RESULTS AND DISCUSSION

External P Requirements

According to the yield response curves presented in Figure 6.1, the external P requirements of all three varieties of *C. esculenta* were 0.002 ppm P in solution. These results coincide with the unpublished results of Fox and de la Pena. They obtained no significant yield response to P by flooded taro grown in plots in which the minimum soil solution concentration was 0.02 ppm. Bun Long produced the highest yields with a maximum of 51 T/ha. Yield was 75 percent of the maximum attained at the lowest P level employed (0.002 ppm). Bray 1 solution extracted less than one ppm from the soil of this treatment. Lehua produced yields up to 37 T/ha. The shape of the response curve was similar to the one for Bun Long. The yield response for dasheen ascended more steeply, however the yields were lower. The lowest P treatment produced only 50 percent of the maximum yield, indicating that this variety of dasheen was more sensitive to low P levels than the other varieties.

Internal P Requirements

The leaf P percentage of all three varieties increased with increasing P in solution (Table 6.2). About 0.40 percent P in the leaf blades is associated with 95 percent of maximum yield (Fig. 6.2). This is similar to the level found by Fox and de la Pena under flood conditions (0.41 percent P).

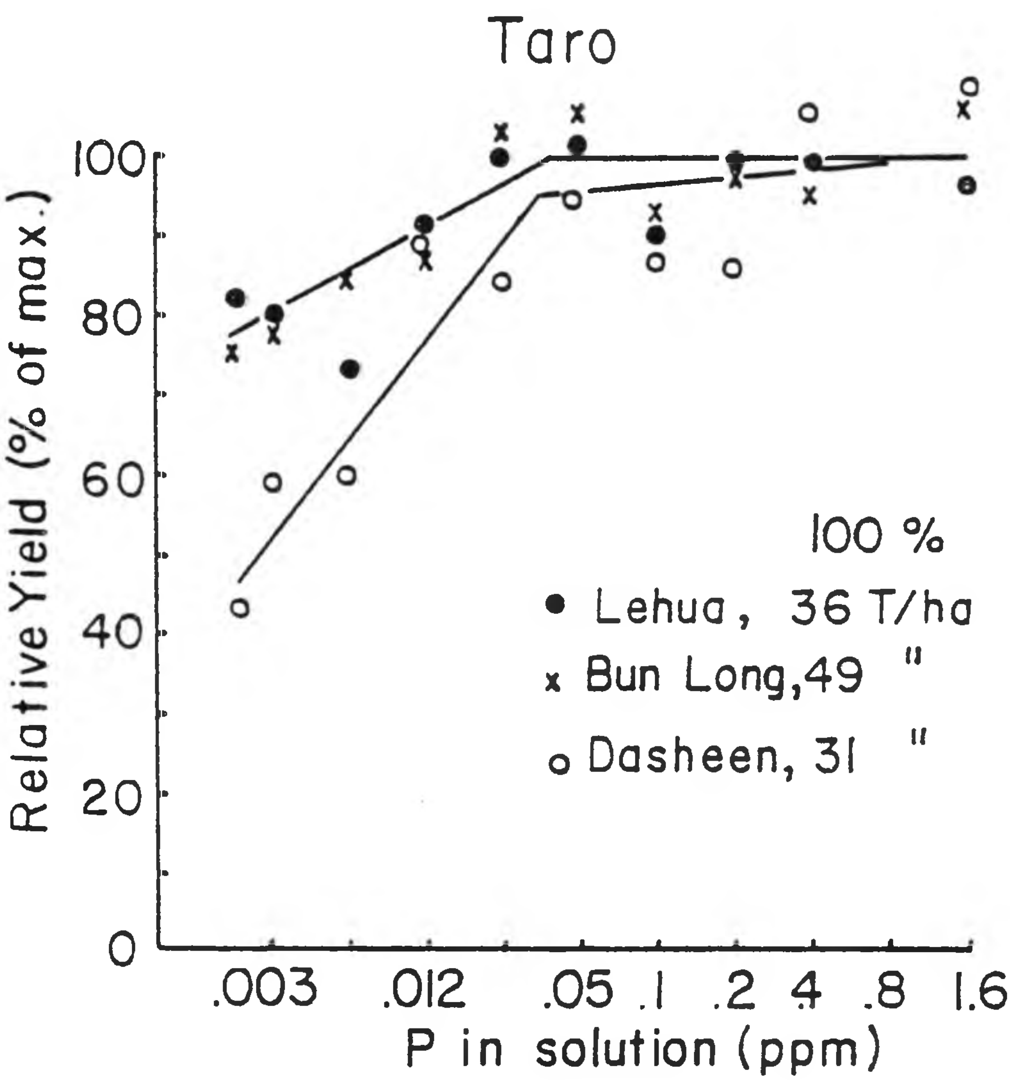

Figure 6.1 A composite yield response curve for the varieties Lehua and Bun Long and a yield response curve for dasheen as a function of P in solution. The correlation coefficients for the ascending portions of the 2 response curves are 0.89 and 0.94 for the Lehua and Bun Long varieties.

Table 6.2

P Concentration in the Leaf Blades of Three Varieties of *C. esculenta* as a function of P Established in Solution

P Level Maintained in the Soil (ppm)	Percent		
	Lehua	Bun Long	Dasheen
.002	.29	.25	.24
.003	.37	.31	.33
.006	.39	.32	.36
.012	.38	.32	.34
.025	.41	.35	.34
.05	.45	.35	.36
.1	.47	.39	.37
.2	.56	.45	.39
.4	.59	.50	.45
1.6	.66	.58	.42

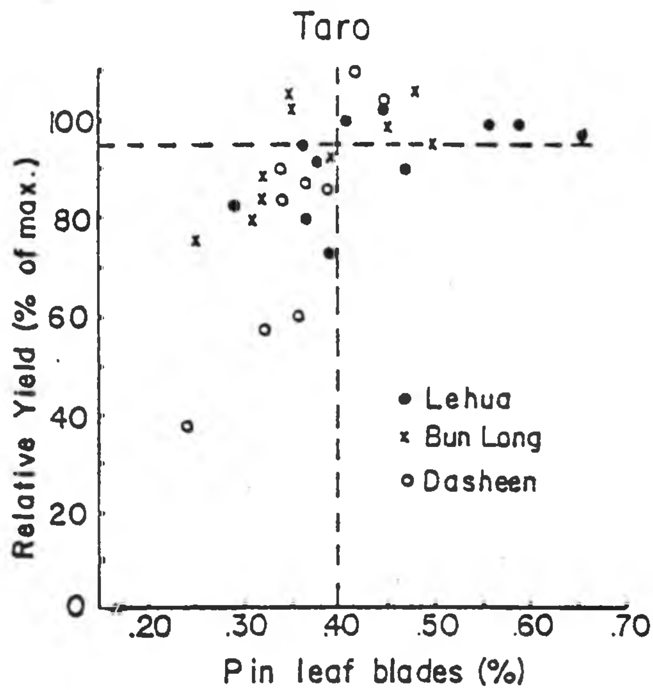

Figure 6.2 Relative yield of three varieties of taro grown on Kauai as influenced by the P concentration in the leaf blades sampled at 3 months after planting

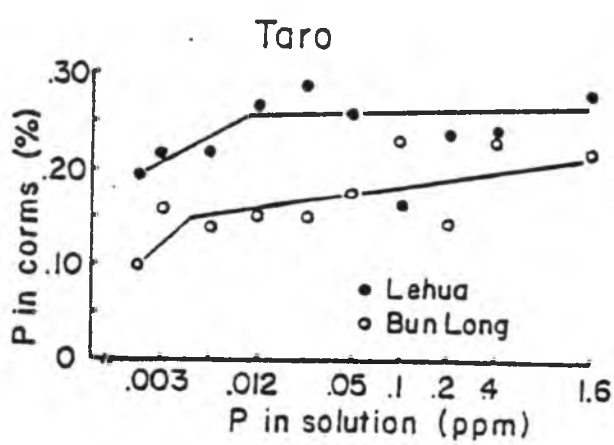

Figure 6.3 P concentration in the corms of two taro varieties grown on Kauai as influenced by the concentration of P in solution

Phosphorus concentration in corms was a good indicator of the P requirements for near maximum yield (Fig. 6.3). Phosphorus increased from 0.18 percent P associated with the lowest P treatment to 0.26 at 0.012 ppm P in solution. The curve was flat beyond 0.012 ppm P for Lehua. Bun Long has not only a lower concentration of P in the corms but also a more gradual increase with increasing P in solution.

The Contribution of Mycorrhizae to the P Nutrition of Taro

At three months of age root samples were taken and inspected for VA mycorrhizal infection. At the low P treatments the percentage of the root cortex infected with mycorrhizae was approximately 10 percent for all three varieties. Infection was less at the highest P level and in the case of Lehua there was no infection.

At harvest Bun Long and Lehua were inspected and the amount of infection was constant for all the P treatments with Lehua having approximately 10 to 15 percent and Bun Long having approximately 5 to 10 percent. These levels of infection are low in comparison with cassava and yams. Taro has evolved under flood conditions and therefore one would not expect it to be a strongly mycorrhizal plant.

The Influence of P on Other Nutrients

Increased P fertilization did not influence the concentration of other nutrients in the leaves. In Table 6.3 the concentrations are presented for the 0.012 ppm P in solution treatment, the P treatment which produced near maximum yield.

Table 6.3

Nutrient Levels in Leaf Blades (3 Months after Planting) and in the Corms at Harvest for Three Varieties of *C. esculenta* for the 0.012 ppm P in Solution Treatment Grown on Kauai

Variety	Percent					ppm			
	N	K	Ca	Mg	S	Mn	Fe	Cu	Zn
(leaves)									
Lehua	3.8	5.6	2.3	.20	.32	170	125	23	42
Bun Long	3.8	5.1	3.0	.38	.39	200	87	21	41
Dasheen	3.8	5.5	2.7	.29	.35	130	92	21	42
(corms)									
Lehua	.45	1.2	.20	.03	.02	-	-	-	-
Bun Long	.69	1.4	.13	.07	.04	-	-	-	-

SUMMARY

Taro yields were near maximum at 0.02 ppm P in solution while 75 to 80 percent of maximum was obtained for Lehua and Bun Long at 0.002 ppm P in solution which is less than one ppm using Bray 1. Dasheen responded more dramatically to the first increments of P. Internal P concentrations in the leaf blades of 0.40 percent are associated with 95 percent of maximum yield. Mycorrhizal infection was very low and it would appear to contribute only slightly to the P nutrition of the plant. The very extensive root system appears to be a major reason for taro being able to utilize relatively low levels of P.

CHAPTER VII

THE COMPARATIVE P REQUIREMENTS OF ROOT CROPS AND IMPLICATIONS IN THE TROPICS

INTRODUCTION

This chapter will focus on the comparative P requirements of the five root crops. The composite P yield response curves for the five root crops will be compared to evaluate the production influence of P inputs on energy and protein of each of the crops. This will be discussed at optimum P levels for each of the crops and also at a soil P level that is frequently encountered in the tropics. Finally, a survey is made of the P status and the P requirements of some important soils in the tropics and it it observed how the crops grown there seem to lie within fertility boundaries. Although this information is very general in nature it should be useful to planners for evaluating which crop should be cultivated on certain soils.

COMPARATIVE P REQUIREMENTS OF ROOT CROPS

The yield response of the five root crops varied considerably with P fertilization. The response curves presented in Figure 7.1 are composites for various locations where the individual crops were grown. The number of experimental locations for the various crops presented in Figure 7.1 are as follows: cassava, 7; potatoes, 5, sweet potatoes, 3; taro, 1 (3 varieties); and yams, 5. The generated response curves relating relative yield (R.Y.) to predicted P concentration were as follows:

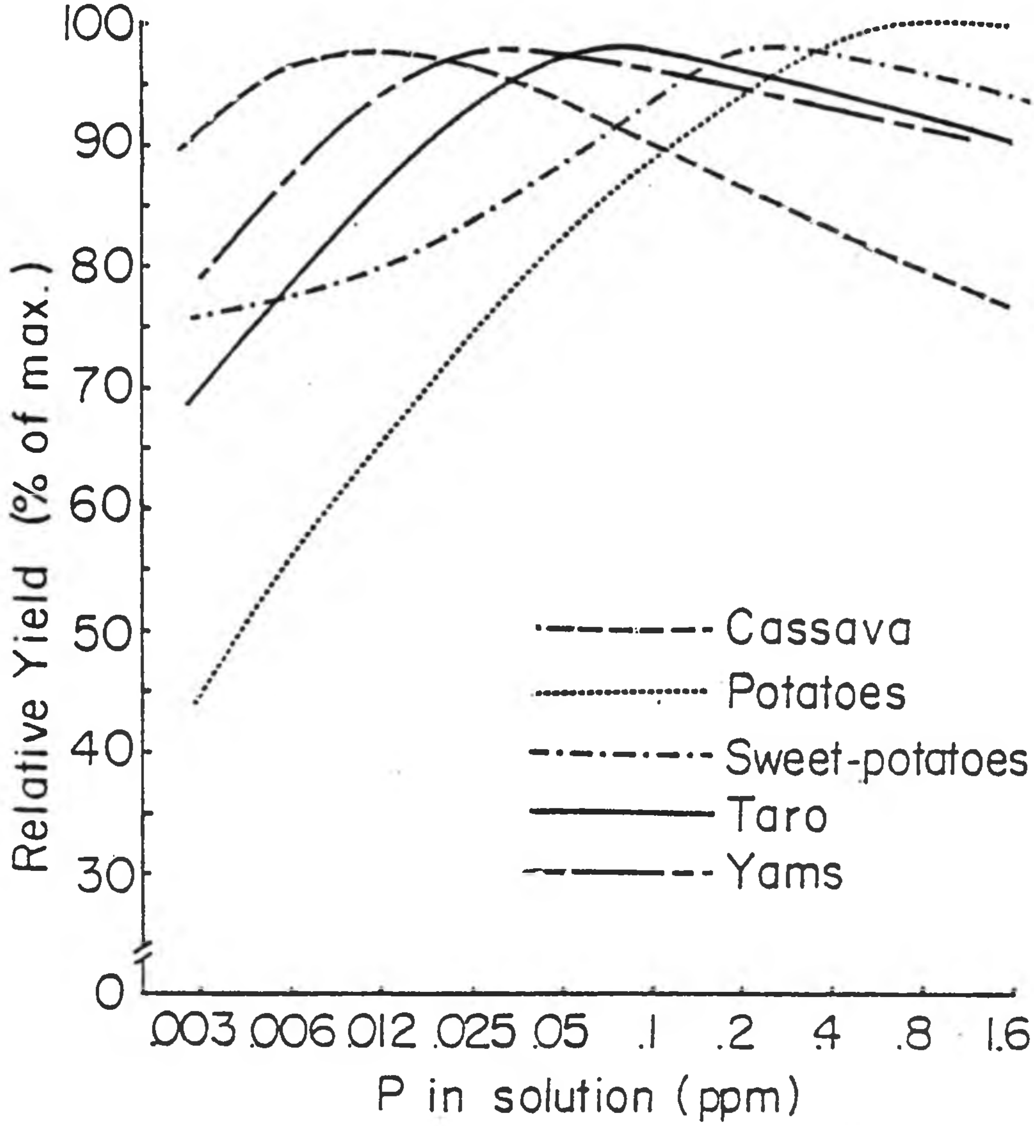

Figure 7.1 Comparative P requirements for five root crops grown on various soils throughout the world. The yield response curve for each crop was a composite of the following number of experiments giving the following correlation coefficient values: cassava, 7 experiments, $R^2 = 0.49$; potatoes, 5 experiments, $R^2 = 0.81$; sweet potatoes, 3 experiments, $R^2 = 0.71$; taro, 1 experiment with 3 varieties, $R^2 = 0.61$ and yams, 5 experiments, $R^2 = 0.47$.

Cassava: $R.Y. = 206 + 351\ P^{*} + 38 \log P - 365\ P^{\frac{1}{2}} - 94\ P^{2}$

Potatoes: $R.Y. = 2 - 6.81\ P + 61.1\ (\log P \cdot 1000)^{\frac{1}{2}}$

Sweet potatoes: $R.Y. = 71 - 63\ P + 86\ P^{\frac{1}{2}} + 5.2\ P^{2}$

Taro: $R.Y. = 174 + 64\ P + 38 \log P - 141\ P^{\frac{1}{2}}$

Yams: $R.Y. = 207 + 200\ P + 45 \log P - 269\ P^{\frac{1}{2}} - 39\ P^{2}$

The generated response curves were highly correlated (one percent level) with the yield data for the various locations for each crop. Values for R^2 ranged from almost 0.5 for cassava and yams, the least responsive species, to 0.8 for potatoes, the most responsive species (see caption to Fig. 7.1).

FACTORS INFLUENCING THE YIELD RESPONSE TO P

Genetic Factors

Even though potato, sweet potato and cassava originated in South America, they undoubtedly developed under different climatic and soil conditions. Potatoes were taken from the high altitude tropics of South America to Europe and later to North America. Through selection and breeding, they became a high yielding crop for high fertility conditions. Results in Figure 7.1 clearly show that the potato does not grow well under low P conditions.

The sweet potato originated in the lowland tropics of South America. It has become a major staple food in Southeast Asia, with China producing 75 percent of the world's crop. Sweet potato is usually grown on sandy soils in Southeast Asia. Until the past decade little plant breeding

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* P refers to the estimated P in solution as determined by P sorption curves.

on sweet potatoes has been done except in the southern USA. Sweet potatoes are rather well adapted to low fertility conditions with 75 to 80 percent of maximum yield obtained at the lowest P level we have imposed (Fig. 7.1).

Cassava, which like sweet potato originated in the lowland tropics of South America, has remained a major food crop there. It has become a major crop of West Africa and to a lesser extent in Asia. Only in recent years has there been any research work on breeding improved cassava varieties. The breeding work is considering fertility as an important parameter.* Cassava is frequently a crop grown in sequence with upland rice and corn, with cassava being the last crop in the sequence. Cassava has a reputation of being a crop with low nutrient requirements because it succeeds after other crops have used the flush of nutrients that are mobilized following land clearing from forest. The yield response curve in Figure 7.1 shows that near maximum yields of cassava can be obtained at extremely low P levels. In fact, cassava yields decreased with increased P levels beyond 0.025 ppm P. It was observed that at high P levels there was excessive vegetative growth at the expense of root development.

Yams and taro both are believed to have originated in Southeast Asia. Some species of yams are also believed to have evolved in West Africa where yams are an important food crop. Yams have not received much research attention. The cultivars being grown were naturally selected in the environments where they grow best. Yams are not as

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* CIAT Annual Report. Cassava Production Systems 1977.

efficient as cassava in utilizing low levels of P (Fig. 7.1).

Taro evolved under lowland wet or flooded soil conditions. It is known that under flooded conditions iron phosphates may become soluble. Thus, under flooded conditions P concentration may increase three to four fold so that soils which would otherwise be deficient in P are not (Fox and de la Pena 1971, unpublished data). However, under upland conditions, as was the case in the experimental results for taro presented in Figure 7.1, the P levels were low and remained so. Taro responded to the first increments of P applied as fertilizer when these conditions prevailed.

Length of the Growing Season

The growing seasons for the root crops investigated here varied three fold, from 4 to 12 months. For the experiments in Hawaii the lengths of the growing seasons were as follows: potatoes, 120 days; sweet potatoes on Kauai, 150 days; yams, 225 days; taro, 270 days and cassava, 365 days. For this set of data with one minor exception the P requirements are inversely related to the length of the growing season (Fig. 7.1).

Root System and Mycorrhizal Association

Although no quantitative root studies were done in this project some interesting observations were made. Generally the longer the growing season the more extensive the root system.

It is well established that the root system of the potato plant is small and generally limited to the surface horizon. Swaminathan and Verma (1977a) noted that the earlier maturing varieties had most of their roots in the surface 10 cm while later maturing varieties had a more widely distributed root system. Not only do potatoes have a limited root system but they also have a low percent of root infection with endomycorrhizal fungi (Swaminathan and Verma 1977b). They noted that only in 23 percent of the potato fields surveyed was there any root infection with mycorrhiza. These two factors offer possible explanations for the relatively high P requirements of potatoes.

The root system of taro is extensive, exploring a large volume of soil. Because taro is a plant which usually grows in flooded (anaerobic) soils, extensive mycorrhizal associations are not expected. However, the upland (non-flooded) taro was occasionally infected. Thus it is not surprising that the external P requirement of upland taro was similar to flooded taro. The results in Figure 7.1 indicate that upland taro does respond to P fertilization up to about 0.025 ppm P in solution.

Cassava originated in tropical South America where the soil P levels were low. Under these conditions it is not surprising that the crop developed an extensive root system and a strong mycorrhizal association, and that the P requirements of field-grown cassava are among the lowest for root crops investigated (Fig. 7.1).

Roots of yams are not as extensive as roots of cassava; however, yams do develop a strong mycorrhizal association. Thus yams efficiently utilize low levels of soil P. Roots are a prerequisite to mycorrhiza, however. Thus, yams are not as efficient as cassava in P uptake, which results in yams having a higher P requirement than cassava (Fig. 7.1).

Little is known about the degree of mycorrhizal association of sweet potatoes. However, that they have an efficient mycorrhizal association is suggested because sweet potatoes utilize P very well in a relatively short growing season. The lack of response to increased P fertilization up to 0.025 ppm P is noteworthy. Yost and Fox (1979) have speculated that a plateau in the yield response curve, as noted in the case of sweet potatoes, indicates that the contribution of P to the plant by mycorrhiza is diminishing as the P concentration in the external solution is increasing. A plateau is reached when P uptake by the non-mycorrhizal roots increases only slightly faster than the decrease in the contribution being made by the mycorrhiza. The general slope of the sweet potato curve (Fig. 7.1) and a logical extrapolation of this curve backward to very low concentrations of P in solution can lead to only one conclusion: the threshold concentration for P uptake by sweet potatoes must be exceedingly low.

COMPARATIVE ENERGY AND PROTEIN PRODUCTION OF ROOT CROPS

An extensive study on the importance of potatoes as a producer of energy and protein in the tropics has been made by Van Der Zaag (1976). For his comparative study he used average crop yields for countries between 30° north and south latitude. He concluded that potatoes produced more protein than the major root, cereal and grain legume crops on a per hectare, per day basis. Sweet potatoes and potatoes produced equal amounts of energy per hectare, per day, both being superior to other major crops. This evidence, taken at face value, suggests that potatoes should be considered as an important crop in the tropics.

Based on the composite yield response curves in Figure 7.1 there is considerable variation in the response of the five root crops to P.

Energy and protein production will be predicted at the most favorable level for each of the crops and also at a soil P level of 0.005 ppm, a level which is common in the tropics. Various assumptions have been used for making these predictions. These are presented in Table 7.1.

At optimum P nutrition, sweet potatoes produced the greatest amount of energy per hectare, per day followed by potatoes. Protein production was maximum for potatoes while sweet potatoes were a distant second (Table 7.1). Cassava produced low quantities of protein and was only slightly better than yams with respect to energy production. Taro ranked third in both protein and energy production.

The estimated yields at a P in solution level of 0.005 ppm, a value which is generally found in soils of the tropics, is also an important consideration. Based on Figure 7.1 the relative yield at 0.005 ppm P was determined. Using these data the estimated yields under these experimental conditions are given in Table 7.2. The energy and protein productions at this low level of P, as presented in Table 7.2, place sweet potatoes as number one for energy production with cassava in second place followed by taro, potatoes and yams. Protein production, even at these low P levels, was still highest for potatoes even though relative yield of the potatoes was only 54 percent of maximum (Table 7.2).

The above results, however, may not be a realistic evaluation. For potatoes, the cost of good seed, irrigation and other major inputs are major constraints. Also potatoes are susceptible to fungal, viral and bacterial diseases. Furthermore, potatoes are intolerant of adverse weather or fertility conditions. Cassava and taro both require lower inputs and also are grown for the leaves which are rich in protein,

Table 7.1

Comparative Energy and Protein Production of 5 Root Crops at Optimum P Fertility for Each Crop Respectively

Crop	Number of Expts.	Average Maximum Yield (T/ha)	Length of Growing Season (days)	Avail. Energy* per 100 grams	Energy Production day^{-1} ha^{-1} 10^3kJ	Protein Content (percent)	Protein** Production day^{-1} ha^{-1}	P in Solution Required (ppm)
Potatoes	5	35	120	310	768	2.0	4.9	0.2
Cassava	7	31	365	633	457	0.7	0.5	0.005
Sweet Potatoes	3	31	150	472	829	1.5	2.7	0.1
Yams	5	25	225	430	417	2.0	1.9	0.025
Taro	1	39	270	468	575	1.8+	2.2	0.02

* Based on an edible portion of 85 percent, available energy and protein content are taken from de Vries et al. (1967).

** Protein production in kilograms.

\+ Estimated, based on de Vries et al. (1967).

Table 7.2

Comparative Energy and Protein Production of 5 Root Crops at 0.005 ppm P in Solution. Yields are based on average yields for a number of experiments and estimating yields based on the yield response curves in Figure 7.1.

Crop	Number of Expts.	Relative Yield (percent of max.)	Estimated Yield (T/ha)	Energy Production $day^{-1}\ ha^{-1}\ 10^{3}kJ$	Protein Production* $day^{-1}\ ha^{-1}$
Potatoes	5	54	19	417	2.7
Cassava	7	95	31	457	0.5
Sweet Potatoes	3	78	24	641	2.1
Yams	5	86	22	367	1.7
Taro	1 (3 var.)	78	30	442	1.7

* Protein production in kilograms.

minerals and vitamins. In this study no consideration was given to the amount of food value that there is in the leaves of these two crops which are widely consumed.

COMPARING THE P STATUS OF IMPORTANT TROPICAL SOILS AND THE ROOT CROPS GROWN

Soil samples collected from various countries in the tropics have been utilized in constructing P sorption curves using the standard technique as described in the section on general methods. Table 7.3 gives a summary of the P requirements to obtain 0.01, 0.02 and 0.2 ppm P in solution. In this work it appears that 0.005 ppm P is a reasonable mean value for P found in most soils in the tropics. Phosphorus required to obtain 0.01, 0.02 and 0.2 ppm P in solution varies tremendously among soils but insofar as soils within an area or country are similar a summation of data may be useful. Countries with low P requirements are represented by alluvial soils (as in Bangladesh, Peru and Taiwan) or sandy soils (as in Ghana, Togo and the savanna region of Nigeria). The soils in West Africa are classified as Alfisols. Soils in the countries with high rainfall are generally highly weathered, being Ultisols or Oxisols (as in Colombia, Zaire, Sierra Leone, Indonesia and Malaysia). High P requiring soils are those of volcanic ash origin (as in Mt. Cameroon, Mt. Kenya and New Guinea).

Areas of root crop production somewhat follow the P requirement index. Potatoes are grown extensively in Peru and Bangladesh. Sweet potatoes are grown extensively in Bangladesh, India and Taiwan. These soils have a relatively low P requirement. The soils with higher P

Table 7.3

Phosphorus Requirements Based on P Sorption Curves for Important Soils in Various Countries Throughout the Tropics

Country	Phosphorus Required (μg/g) to obtain the following levels in soil solution (ppm) .01	.02	.2	Number of Samples	Range for .01	.02	.2
Australia	57	110	300	28	0–200	0–500	15–650
Bangladesh	14	24	80	8	0–50	0–75	35–200
India	10	36	175	9	0–50	0–100	65–500
Indonesia	60	110	270	8	15–120	25–200	70–550
Malaysia	54	92	275	13	30–110	45–200	120–440
New Guinea	85	340	1880	4	30–170	180–500	1500–2200
Taiwan	3	8	50	55	0–40	0–40	4–165
Thailand	29	64	163	8	0–60	6–110	20–340
Cameroon (Savannah)	18	43	133	2	10–25	35–50	115–280
Cameroon (Mt. Cameroon)	0	0	1300	1			
Ghana	4	9	53	11	0–20	0–65	12–170
Nigeria (Savannah)	6	13	34	8	0–6	5–30	23–55
Nigeria (S.E.)	13	32	108	26	0–70	0–100	0–400
Kenya (Mt. Kenya)	0	160	800	6	0	0–370	220–1600
Kenya (Muka Muku)	1	25	170	7	0–8	10–90	100–440
Sierra Leone	9	39	270	4	0–25	0–70	130–400
Tanzania	1	5	88	6	0–10	0–30	0–210
Togo	2	5	14	6	0–8	0–12	0–25
Zaire	20	55	180	10	5–40	25–110	70–400
Zambia	12	52	70	5	0–25	0–50	30–150
West Indies	35	80	260	20	0–100	0–175	70–1000
Colombia (Llanos Orientales)	45	100	420	12	0–110	0–300	25–1650
Peru	6	9	110	4	0–25	0–35	15–300

requirements, but which are low in P, are where cassava predominates (Zaire, Colombia and Sierra Leone). Yams and cassava also are grown along with taro on the Alfisols of West Africa. However, under these climatic conditions and with the existing farmers' management skills the utility of growing potatoes would be low.

A HYPOTHETICAL EXAMPLE OF THE ECONOMICS OF P FERTILIZATION ON TWO SOILS WITH DIVERSE SORPTION CHARACTERISTICS

A hypothetical example of the economics of P fertilization was worked out. Two soils with diverse sorption characteristics were selected. Soil A (Quartzi-psamment) is from Thailand and Soil B (Aquic Tropudult) is from Indonesia; data from both are presented in Figure 4.1. To obtain P levels of 0.005, 0.02, 0.1 and 0.2 ppm in solution Soil A requires: 2, 7, 15 and 20 μg P/gram of soil while Soil B requires: 50, 180, 360 and 480 μg P/gram of soil. For this comparative study several assumptions were made: (1) The cost of P fertilizer as Treble Super Phosphate is $300 per ton. (2) There is no residual value of the P fertilizer applied. (3) The value of one ton of any of the harvested root crops is $80. (4) No consideration was given to the energy and protein production. (5) The length of the growing season was not considered. (6) Yields were based on those in Table 7.1 and the shape of the response curve in Figure 7.1.

Taro is the most economical crop to grow on Soil A at optimum P fertilization (Table 7.4). Potatoes ranked second followed by cassava, sweet potatoes and yams. At a P in solution level of 0.005 ppm, cassava produced the greatest economic return. Taro ranked second followed by

Table 7.4

A Hypothetical Example of the Economics of P Fertilization at Optimum and Suboptimal Rates for the Various Root Crops on Two Soils with Diverse Sorption Characteristics

Crop	P in Solution Required for Optimum Yield (ppm)	P Fertilizer Required to Obtain Desired P Level (µg P/g soil)		Fertilizer Cost/ha (US Dollars)		Yield at Optimum P Fertilization (T/ha)	Yield at .005 ppm P (T/ha)	Gross Income at Optimum P, .005 ppm P* (US Dollars)		Gross Returns after P Fertilizer Costs Are Deducted** (US Dollars)			
		Soil A	B	Soil A	B					Soil A Opt.	Soil A .005	Soil B Opt.	Soil B .005
Cassava	.005	2	50	6	150	31	31	2480	2480	2474	2474	2330	2330
Taro	.02	7	180	21	540	39	30	3120	2400	3099	2394	2580	2250
Sweet Potatoes	.1	15	360	45	1080	26	24	2080	1920	2035	1914	1840	1770
Yams	.02	7	180	21	540	25	22	2000	1760	1979	1754	1460	1610
Potatoes	.2	20	480	60	1440	35	19	2800	1520	2740	1514	1360	1370

* Assuming a market price of 80 US Dollars per ton.

** Fertilizer P costs to obtain .005 ppm P are $600 for Soil A and $150 for Soil B.

sweet potatoes, yams and potatoes. On Soil A it is economically feasible to fertilize each crop to its optimum P in solution requirement. The low sorption capacity of Soil A makes it possible to fertilize a crop of potatoes to 0.2 ppm P with a greatly increased return over the sub-optimal P level (Table 7.4).

On Soil B, which has a high P sorption capacity, taro was the best crop to grow at optimum P fertilization followed by cassava, yams, potatoes and sweet potatoes. Economic returns from all the crops were greatly reduced in comparison with returns from the optimum P fertilization rates for Soil A. At 0.005 ppm P, cassava ranks first followed by taro, sweet potatoes, yams and potatoes. Taro benefits from P fertilization to 95 percent of maximum level while it is not economic to fertilize potatoes, yams and sweet potatoes to their respective requirements for 95 percent of maximum yields (Table 7.4). Sweet potatoes have a very flat yield response curve (Fig. 7.1) and thus on a high P sorbing soil the cost of the added P fertilizer is greater than the returns from the increase in yield (Table 7.4). This simplified illustration demonstrates that the P sorption capacity of a soil is an important economic consideration in determining which crop to grow and the quantity of P fertilizer to apply.

SUMMARY

The yield response of the five root crops varied considerably with P fertilization. Factors which influenced the comparative P requirements of these root crops included: (1) genetic factors which were influenced by the place of origin and the adaptation of these crops to new environments over time. (2) Crop duration was important. With one minor exception the P requirements are inversely related to the length of time required to produce the crop. (3) The extent of the root system and the role of mycorrhiza seem to be important factors in the efficient utilization of small quantities of P by cassava and to a lesser extent by yams. Potatoes with a less extensive root system and a low mycorrhizal infection have a very high P requirement. Potatoes and sweet potatoes were the most productive in protein and energy production, respectively, on a per hectare, per day basis. The economics of root crop production depends on many factors but the P requirements of the root crops along with the P sorption capacity of a soil are important considerations and these should be considered simultaneously. Prior to introducing new crops into areas where they are not being grown the factors discussed in this chapter need to be considered. In particular it is essential that the nutritional requirements should be compatible with the nutrient supply.

PART III

Appendix Table 1

Nutrient Levels in Leaf Blades of Potatoes for the Wahiawa Experiment at 58 and 100 Days after Planting

P Treatment	58 Days				100 Days				58 Days				100 Days			
	K	Na	Ca	Mg	K	Na	Ca	Mg	Mn	Fe	Zn	Cu	Mn	Fe	Zn	Cu
1	6.6	.08	1.5	.45	5.5	.09	2.1	.46	908	340	94	23	1880	142	210	15
2	5.8	.08	1.0	.48	6.2	.15	1.4	.41	690	260	66	28	2280	170	300	30
3	5.7	.04	.8	.48	6.3	.14	1.3	.51	764	150	74	23	2160	210	270	33
4	6.2	.07	1.1	.48	5.7	.10	1.6	.49	734	240	74	28	1940	142	194	30
5	6.4	.09	1.1	.53	5.6	.08	1.3	.46	720	255	80	30	1680	110	170	20
6	5.3	.07	.8	.46	5.8	.12	1.3	.46	588	190	76	20	2000	124	224	20
7	5.2	.07	.8	.44	5.3	.10	1.4	.48	586	124	70	18	2050	124	190	20
8	5.0	.04	.9	.49	5.4	.13	1.6	.58	486	124	78	30	2280	124	256	18
9	6.9	.09	1.4	.56	4.4	.09	1.6	.58	600	190	78	25	1330	115	154	15
10	8.5	.11	1.6	.70	4.4	.06	1.1	.43	680	253	150	30	1960	115	180	15
MEAN	6.2	.08	1.1	.50	5.5	.10	1.5	.49	676	213	75	26	1956	138	215	22

Appendix Table 2

Nutrient Levels in Leaf Blades of Potatoes for the Kauai Experiment (lime treatments) at 58 and 100 Days after Planting

Treatment	58 Days			100 Days			58 Days			100 Days		
	K	Ca	Mg	K	Ca	Mg	Mn	Fe	Cu	Mn	Fe	Cu
1	6.1	1.3	.30	7.1	1.5	.15	153	298	31	1230	212	29
2	6.7	1.4	.32	7.0	1.5	.17	280	491	35	1344	273	30
3	7.2	1.6	.33	6.7	1.7	.20	177	326	36	1605	169	34
4	6.7	1.7	.36	6.6	2.1	.24	169	276	32	1623	133	36
5	6.4	1.7	.34	6.0	2.2	.32	94	174	33	1326	105	37
6	6.4	1.7	.34	6.2	2.4	.29	142	162	32	1474	105	34
7	5.9	1.7	.32	5.8	2.6	.28	126	172	31	1231	124	35
8	6.4	2.1	.33	5.8	2.6	.25	120	309	30	1400	115	35
9	6.0	1.6	.30	6.3	2.8	.30	82	129	29	804	223	33
10	5.4	1.9	.29	6.0	3.0	.29	78	127	29	1426	108	26
MEAN	6.3	1.7	.32	6.4	2.2	.25	142	246	32	1346	157	33

Appendix Table 3

Nutrient Levels in Petioles of Potatoes for the Kauai Experiment (lime treatments) at 58 and 100 Days after Planting

P Treatment	Percent						ppm					
	Age 58 Days			Age 100 Days			Age 58 Days			Age 100 Days		
	K	Ca	Mg	K	Ca	Mg	Mn	Fe	Cu	Mn	Fe	Cu
1	12.5	1.1	.19	10.3	1.9	.18	77	363	43	328	240	87
2	11.9	1.1	.20	10.3	1.8	.14	105	490	50	416	325	86
3	12.6	1.2	.17	10.4	1.9	.17	87	291	50	421	192	72
4	11.9	1.3	.19	9.7	2.2	.26	73	228	44	362	135	73
5	11.9	1.2	.16	9.2	2.1	.31	49	174	41	275	105	72
6	11.5	1.2	.16	9.2	2.3	.27	61	157	41	314	108	71
7	11.1	1.3	.16	8.3	2.4	.27	55	148	41	232	139	68
8	10.7	1.5	.16	7.9	2.9	.24	64	263	40	248	155	61
9	10.6	1.3	.15	7.8	2.6	.26	70	129	34	167	287	78
10	10.4	1.4	.15	7.7	2.8	.23	47	192	40	265	139	46
MEAN	11.5	1.3	.17	9.1	2.3	.23	66	244	42	303	183	71

Appendix Table 4

Total Nitrogen of Potato Leaf Blades
(measured as percent on oven dry basis)

Treatment (ppm P in Solution)	58 Days		100 Days	
	Wahiawa	Kauai	Wahiawa	Kauai
.025	6.0	3.0	2.6	1.4
.1	7.0	2.6	2.6	1.6
1.6	6.8	2.8	2.6	1.6

Appendix Table 5

Nutrient Analysis of Potato
Tubers Grown at Wahiawa
(on dry weight basis)

P Treatment	Percent				ppm			
	K	Na	Ca	Mg	Mn	Fe	Zn	Cu
1	1.7	.02	.09	.13	44	25	20	8
5	1.6	.02	.04	.13	14	25	22	9
8	1.4	.02	.03	.13	14	25	14	13
10	1.2	.02	.05	.13	22	18	16	9

Appendix Table 6

Nutrient Levels in Soil
Prior to Planting Potatoes
(in me/100 grams)

	Potassium	Sodium	Calcium	Magnesium
Wahiawa	.75	.44	6.6	1.8
Kauai	.21	.33	8.2	.75

Appendix Table 7

Yield Response of Sweet Potatoes to Phosphorus
Grown on Kauai (T/ha)

Treatment	Replication	ppm P	Yield (T/ha)		
			Lime	Slag	Combined
1	II	.002	25.8	31.8	28.8
2	III	.004	26.9	27.9	27.4
3	I	.007	30.3	24.7	27.5
	II		33.8	30.7	32.3
4	I	.03	33.9	46.7	40.3
	II		33.3	36.0	34.7
	III		35.5	27.3	31.4
5	I	.05	33.3	34.4	33.9
	II		35.0	31.4	33.2
	III		28.0	32.1	30.1
6	I	.13	41.4	29.0	35.2
	II		39.0	41.0	40.0
	III		32.2	41.1	36.7
7	I	.34	41.4	43.4	42.4
	II		35.1	28.1	31.6
	III		23.9	29.9	26.9
8	I	.72	24.7	47.5	36.1
	II		32.4	34.3	33.4
9	II	1.55	36.2	37.8	37.0
10	III	5.5	27.5	33.0	30.2

Appendix Table 8

Nutrient Levels in Leaves† of Sweet Potatoes
(lime and slag combined) Grown on Kauai
(percent on oven dry basis)

Treatment		N*		K		Ca		Mg		S	
	ppm P	58 days	79 days	58 days	79 days	58 days	79 days	58 days	79 days	58 days	79 days
1	.002	3.13	2.74	4.32	4.14	.79	.65	.22	.23	.24	.25
2	.004	3.06	3.02	4.52	4.10	.71	.67	.21	.23	.25	.24
3	.007	3.39	3.10	4.66	3.87	.85	.62	.22	.23	.25	.24
4	.03	3.42	3.52	4.44	3.87	.88	.74	.24	.26	.26	.26
5	.05	3.33	2.76	4.74	3.91	.98	.72	.24	.25	.25	.24
6	.13	3.74	3.08	4.49	3.90	1.03	.75	.24	.26	.27	.26
7	.34	3.49	2.83	4.60	3.65	1.02	.69	.24	.26	.26	.25
8	.72	4.21	3.10	4.43	3.82	1.09	.77	.24	.24	.26	.26
9	1.55	3.61	2.82	4.21	3.71	1.08	.90	.22	.25	.25	.25
10	5.5	3.86	3.13	4.42	3.68	1.48	.85	.25	.25	.27	.24

† At 58 days leaf blades and at 79 days leaf blades and petioles were analyzed.

* N levels are for lime treated plots only.

Appendix Table 9

Nutrient Levels in Tubers of Sweet Potatoes Grown on Kauai in Response to Increasing P in the Soil Solution

Treatment ppm P		Percent				ppm	
		N	K	Ca	Mg	Fe	Cu
1	.002	.50	.88	.12	.06	149	12
2	.004	.34	.60	.13	.06	150	10
3	.007	.45	.66	.15	.06	150	11
4	.03	.39	.57	.13	.05	150	10
5	.05	.30	.80	.13	.05	151	13
6	.13	.46	.70	.13	.06	149	11
7	.34	.44	.56	.14	.05	149	11
8	.72	.49	.69	.14	.05	150	11
9	1.55	.41	.61	.13	.05	150	10
10	5.5	.38	.96	.15	.05	140	13

Appendix Table 10

Adjusted Yields of Six Varieties of Cassava (T/ha) Grown on Kauai

	Amarillo			Mameya			Seda			Nina			Ceiba			Pata de Paloma		
Trt	L	S	$\bar{x}$	L	S	$\bar{x}$	L	S	$\bar{x}$	L	S	$\bar{x}$	L	S	$\bar{x}$	L	S	$\bar{x}$
1 II	9.9	12.6	11.3	21.7	10.9	16.3	12.3	15.2	13.8	19.8	23.4	21.6	34.8	44.4	39.6	17.4	10.8	14.1
2 III	12.9	13.4	13.2	16.4	25.2	20.8	8.9	14.6	11.8	14.6	7.2	10.9	45.3	43.8	44.6	9.2	14.9	12.1
3 I	18.5	10.2	14.4	14.3	13.5	13.9	15.6	16.8	16.2	21.0	19.8	20.4	60.6	26.4	43.5	16.8	12.6	14.7
II	17.0	23.4	20.2	24.8	7.2	16.0	19.4	16.7	18.1	22.9	13.2	18.1	40.8	47.5	44.2	26.5	12.4	19.4
4 I	9.9	9.2	9.6	28.9	16.8	22.9	14.1	27.0	20.6	12.9	23.4	18.1	37.8	47.4	42.6	15.6	34.8	25.2
II	16.8	16.8	16.8	26.5	21.8	24.2	9.8	25.7	17.7	16.0	16.5	16.3	41.4	54.6	48.0	12.9	17.4	15.2
III	14.7	8.0	11.4	9.9	11.2	10.6	8.1	20.5	14.3	10.1	12.6	11.4	43.8	34.8	39.3	10.5	21.6	16.1
5 I	21.3	8.6	14.9	32.4	10.8	21.6	23.2	19.7	21.5	16.1	11.0	13.6	42.1	67.5	54.8	16.7	14.3	15.5
II	12.8	15.5	14.2	14.3	18.6	16.5	27.0	12.9	20.0	23.4	11.4	17.4	42.0	48.2	45.6	16.2	9.0	12.6
III	8.8	12.2	10.5	15.9	18.5	17.2	9.2	14.1	11.7	12.6	15.0	13.8	60.0	31.2	45.6	12.6	15.8	14.2
6 I	11.4	10.1	10.8	40.8	17.1	29.0	15.0	22.5	18.8	17.2	19.1	18.2	46.8	48.0	47.4	34.8	13.5	24.2
II	10.0	3.5	6.8	18.4	8.6	13.5	18.6	15.4	17.0	16.5	15.1	15.8	41.0	22.4	31.7	10.2	16.7	13.5
III	16.0	3.2	16.0	16.8	17.6	17.2	19.8	20.4	20.1	15.6	11.9	13.7	51.6	48.0	49.8	31.1	9.5	20.3
7 I	7.6	18.6	13.1	22.4	21.2	21.8	9.2	16.2	12.7	12.6	9.8	11.2	34.6	55.6	45.1	14.4	15.7	15.1
II	12.3	8.6	10.4	15.1	13.0	14.1	15.8	17.1	16.5	16.8	13.5	15.2	45.6	43.4	44.5	15.6	13.2	14.4
III	11.2	16.7	14.0	7.8	11.4	9.6	4.5	9.6	7.1	5.0	8.4	6.7	27.9	41.1	34.5	9.6	9.8	9.7
8 I	13.2	16.5	14.9	18.1	28.2	23.2	16.8	12.6	14.7	18.0	13.9	16.0	37.2	51.0	44.1	12.3	17.3	14.8
II	11.9	12.8	12.4	14.0	21.6	17.8	9.7	8.1	8.9	22.4	13.5	18.0	47.5	25.9	36.7	8.6	13.0	10.8
9 I	12.6	9.3	11.0	17.4	8.5	12.9	16.8	21.6	19.2	17.2	18.8	18.0	31.2	35.7	33.5	9.0	10.8	9.9
10 III	5.1	18.6	11.9	16.1	12.8	14.5	12.3	7.9	10.1	15.2	10.9	13.1	22.8	36.6	29.7	9.8	30.0	19.9
Factor*	1.4	1.1		1.3	.9		1.0	1.1		1.3	1.1		-	-		1.4	1.5	

* Yields were adjusted as the variety Ceiba gave a competitive effect for varieties next to it.
The factor was determined by the ratio of mean yield/plot of plots not next to the variety Ceiba ÷ mean yield/plot of plots next to the variety Ceiba based on the 4 replicated treatments.

Appendix Table 11

Yield Response and Percent P in Leaf Blades as Influenced by P in Solution for Taro Grown under Flood Conditions at the Wailua Experiment Station, Kauai, on a Typic Tropaquept (unpublished data of Fox and de la Pena 1973)

Intended P Level* (ppm)	Determined P Level** (ppm)	P in Leaf Blades+ (percent)	Yield‡ (T/ha)
None	.02	.35	58.3
.003	.05	.36	37.2
.006	.05	.42	59.0
.012	.07	.41	66.2
.025	.16	.41	61.8
.05	.07	.42	62.3
.1	.25	.45	62.7
.2	.30	.39	66.8
.4	.19	.46	63.9
1.6	.39	.42	62.6

* Levels established using P sorption curves.

** Determined 9 months after planting under flood conditions using filter candles.

+ Levels determined at 9 months after planting.

‡ Yields are means of harvests taken at 10, 12 and 14 months after planting.

BIBLIOGRAPHY

Badillo-Feliciano, J. and Lugo-Lopez, M. A. 1976. Effects of four levels of N, P, K and micronutrients on sweet potato yields in an Oxisol. Jour. of Agric. of Univ. of Puerto Rico, 60:597-605.

Banderis, A., Barter, D. H. and Henderson, K. 1976. The use of polyacrylamide to replace carbon in the determination of Olsen's extractable phosphate in soil. J. of Soil Sci., 27:71-74.

Beckwith, R. S. 1964. Sorbed phosphate at standard supernatant concentration as an estimate of the phosphate needs of soils. Aust. J. Exp. Agr. and An. Hus., 5:52-58.

Bishop, R. F., MacEachern, C. R. and MacKay, D. C. 1967. The relation of soil test values to fertilizer response by the potato. IV. Available phosphorus and phosphatic fertilizer requirements. Can. J. Soil Sci., 47:175-185.

Blanchar, R. W., Rehm, G. and Caldwell, A. C. 1965. Sulfur in plant materials by digestion with nitric and perchloric acid. Soil Sci. Soc. Amer. Proc., 29:71-72.

Brown, D. H. 1931. The cultivation of yams. Trop. Agric. (Trin.), 8(8):201-206.

Coursey, D. G. 1968. The edible aroids. World Crops, 20(4):25-30.

Coursey, D. G. and Haynes, P. H. 1970. Root crops and their potential as food crops in the tropics. World Crops, 22(4):261-265.

Edwards, D. G., Asher, C. J. and Wilson, G. L. 1976. Mineral nutrition of cassava and adaptation to low fertility conditions. Proc. 4th Symp. on Trop. Root and Tuber Crops. Cali, Colombia. pp. 124-130.

FAO Production Yearbook. 1974.

Federer, W. T. 1956. Augmented (or Hoonuiaku) Designs. Hawaiian Planters' Rec., 55(2):191-208.

Fox, R. L. 1973. Agronomic investigations using continuous function experimental designs--Nitrogen fertilization of sweet corn. Agron. J., 65:454-456.

Fox, R. L. 1974. Anion and cation absorption by soils. Trop. Agric. (Trin.), 51:200-210.

Fox, R. L. and Kamprath, E. J. 1970. Phosphate sorption isotherms for evaluating the phosphate requirements of soils. Soil Sci. Soc. Amer. Proc., 34:902-907.

Fox, R. L. and Kang, B. T. 1978. Influence of phosphorus fertilizer placement and fertilization rate on maize nutrition. Soil Sci., 125: 34-40.

Fox, R. L., Nishimoto, R. K., Thompson, J. R. and de la Pena, R. S. 1974. Comparative external phosphorus requirements of plants growing in tropical soils. Int. Cong. Soil Sci., Trans., 10th (Moscow), 4:232-239.

Fox, R. L., Plucknett, D. L. and Whitney, A. S. 1968. Phosphate requirement of Hawaiian latosols and residual effects of fertilizer phosphorus. Int. Cong. Soil Sci., Trans., 9th (Adelaide, Aust.), 2:301-310.

Fox, R. L. and Searle, P. G. E. 1978. Phosphate adsorption by soils of the tropics. Am. Soc. Agron. Special Publication, 34:97-119.

Gaztambide, S. and Cibes, H. R. 1975. Nutritional deficiencies of yams (Dioscorea spp.) and related effects on yield and leaf composition. J. of Agric. of Univ. of Puerto Rico, 59:264-273.

Gerdemann, J. W. 1964. The effect of mycorrhizae on the growth of maize. Mycologia, 56:342-349.

Gerdemann, J. W. 1968. Vesicular-arbuscular mycorrhizae and plant growth. A. Rev. Phytopath., 6:397-418.

Geus, J. G. de 1973. Fertilizer guide for the tropics and subtropics. Centre d'Etude del Azote (Zurich), pp. 206-212.

Gilmore, A. E. 1971. The influence of endotrophic mycorrhizae on the growth of peach seedlings. J. Amer. Soc. Hort. Sci., 96(1):35-37.

Godfrey-Sam-Aggrey, W. and Garber, M. J. 1978. Effects of phosphorus and lime on cassava (Manihot esculenta Crantz). J. Agron. and Soil Sci., 146:40-53.

Harlan, J. R. 1976. The plants and animals that nourish man. Scientific American (Sept.), pp. 89-97.

Hodnett, G. E. 1958. A fertilizer experiment on dasheen. Trop. Agric. (Trin.), 35(3):205-207.

Howeler, R. H., Cadavid, L. F. and Calvo, F. A. 1976. The interaction of lime with minor elements and phosphorus in cassava production. Proc. 4th Symp. on Trop. Root and Tuber Crops. Cali, Colombia. pp. 113-117.

Irving, H. 1956. Fertilizer experiments with yams in eastern Nigeria. 1947-51. Trop. Agric. (Trin.), 33:67-78.

Jackson, R. D. and Haddock, J. L. 1959. Growth and nutrient uptake of Russet Burbank potatoes. Am. Potato J., 36:22-28.

Juo, A. S. R. and Fox, R. L. 1977. Phosphate sorption characteristics of some bench-mark soils of West Africa. Soil Sci., 124:370-376.

Kleinschmidt, G. D. and Gerdemann, J. W. 1972. Stunting of citrus seedlings in fumigated nursery soils related to the absence of endomycorrhizae. Phytopathology, 62:1447-1453.

Koli, S. E. 1973. The response of yam (D. rotundata) to fertilizer application in Northern Ghana. J. Agric. Sci., 80:245-249.

Kratky, B. A. and Tamimi, Y. N. 1974. Response of potatoes to phosphorus and windbreak. Hawaii Farm Science, 21/22:10-12.

Landrau, P., Jr. and Samuels, G. 1951. The effect of fertilizers on the yield and quality of sweet potatoes. Jour. of Agric. of Univ. of Puerto Rico, 35(2):71-87.

Lantican, R. M. and Soriano, P. M. 1961. The response of sweet potato to different fertilizer treatments. The Philippine Agriculturalist, 45(5):258-263.

Laughlin, W. M., Martin, P. F. and Smith, G. R. 1974. Lime and P influence Kennebec potato yield and chemical composition. Am. Potato J., 51:393-402.

Lawton, K., Robertson, L. S., Cook, R. L. and Rood, P. J. 1947. A study of correlation between rapid soil tests and response of legume hay to phosphorus and potassium fertilization on some Michigan soils. Soil Sci. Soc. Amer. Proc., 12:353-358.

MacKay, D. C., MacEachern, C. R. and Bishop, R. F. 1966. Optimum nutrient levels in potato leaves. Soil Sci. Soc. Amer. Proc., 30:73-76.

Malavolta, E., Graner, E. A., Coury, T., Brasil Sobr., M.O.C. and Pacheco, J. A. C. 1955. Studies on the mineral nutrition of cassava (Manihot utilissima Pohl). Pl. Physiol., 30:1.

Mekaru, T. and Uehara, G. 1972. Anion adsorption in ferruginous tropical soils. Soil Sci. Soc. Amer. Proc., 36:296-300.

Mitchell, G. A. and McKendrick, J. D. 1975. Volcanic-ash-affected soils of South Central Alaska: Some chemical and mineralogical properties. Agroborealis, 7:21-23.

Mosse, B. 1957. Growth and chemical composition of mycorrhizal and non-mycorrhizal apples. Nature, 179:922-924.

Mosse, B. 1973. Advances in the study of vesicular-arbuscular mycorrhiza. Ann. Rev. Phytopathol., 11:171-196.

Nishimoto, R. K., Fox, R. L. and Parvin, P. E. 1977. Response of vegetable crops to phosphorus concentrations in soil solution. J. Amer. Soc. Hort. Sci., 102(6):705-709.

Obigbesan, G. O. and Agboola, A. A. 1978. Uptake and distribution of nutrients by yams (Dioscorea spp.) in Western Nigeria. Experimental Agric., 14:349-355.

Olsen, S. R. and Watanabe, F. S. 1963. Diffusion of phosphorus as related to soil texture and plant uptake. Soil Sci. Soc. Amer. Proc., 27:648-652.

Ozanne, P. G. and Shaw, T. C. 1968. Advantages of the recently developed phosphate sorption test over the older extractant methods for soil phosphate. Int. Cong. Soil Sci., Trans., 9th (Adelaide, Aust.), 2:273-280.

Peaslee, D. E. and Fox, R. L. 1978. Phosphorus fertilizer requirements as estimated by phosphate sorption. Commun. Soil Sci. Plant Anal., 9(10):975-993.

Phillips, J. M. and Hayman, D. S. 1970. Improved procedures for clearing roots and staining parasitic and vesicular-arbuscular mycorrhizal fungi for rapid assessment of infection. Trans. Br. Mycol. Soc. Am., 20:107-110.

Plucknett, D. L. 1978. Tolerance of some tropical root crops and starch-producing tree-crops to sub-optimal land conditions. ASA special publication "Crop tolerance to sub-optimal land conditions," pp. 125-144.

Plucknett, D. L. and de la Pena, R. S. 1971. Taro production in Hawaii. World Crops, 23(5):244-249.

Powell, C. L. 1974. Potassium uptake by endotrophic mycorrhizas. In: Endo mycorrhizas (F. E. Sanders, B. Mosse and P. B. Tinker, Eds.), pp. 461-468.

Sanders, F. E. and Tinker, P. B. 1973. Phosphate flow into mycorrhizal roots. Pestic. Sci., 4:385-395.

Silva, J. A. 1971. Possible mechanisms for crop response to silicate applications. Proc. Int. Symp. on Soil Fert. Eval. New Delhi. 1:805-814.

Silva, J. R. da and Freire, E. S. 1968. Efeito de doses crescentes de N, P e K sobre a producao de mandioca me solos de baixa e alta fertilidade. Bragantia, 27:357-364.

Smith, F. W. and Cook, R. L. 1953. A study of the relationship between chemically available phosphorus and plant growth response on several Michigan soils. Soil. Sci. Soc. Amer. Proc., 17:26-30.

Swaminathan, K. and Verma, B. C. 1977a. Active root distribution profiles of Indian potato cultivars in relation to their capacity to extract phosphorus from the soil. J. Nucl. Agric. Biol. 6(2):46-48.

Swaminathan, K. and Verma, B. C. 1977b. Symbiotic effect of vesicular-arbuscular mycorrhizal fungi on the phosphate nutrition of potatoes. Proc. Indian Acad. Sci., 85B(5):310-318.

Rendle, C. J. and Kang, B. T. 1976. Phosphorus requirements of three sweet potato cultivars. Proc. 4th Symp. on Trop. Root and Tuber Crops. Cali, Colombia. pp. 117-121.

Rhodes, L. H. and Gerdemann, J. W. 1978. Translocation of calcium and phosphate by external hypae of vesicular-arbuscular mycorrhizae. Soil Sci., 126(2):125-126.

Rudd, C. L. and French, R. J. 1976. Comparison of extraction methods for the determination of available soil phosphorus. Agricultural Record, 3(5):36-40.

Tabatabai, M. A. 1974. Determination of sulphate in water samples. Sulphur Inst. J., 10:11-13.

Tinker, P. B. H. 1975. Effects of vesicular-arbuscular mycorrhizas on higher plants. Symp. Soc. Exp. Biol., 29:325.

Uriyo, A. P. and Kesseba, A. 1973. Response of sweet potatoes to P and K fertilizers on a red Oxisol soil in Tanzania. Beitrage trop. Landwirtsch-Veterinarmed., 11 Jg., H. 3, p. 299-302.

Van Der Paauw, F. 1971. An effective water extraction method for the determination of plant-available soil phosphorus. Plant and Soil, 34:467-481.

Van Der Zaag, D. E. 1976. Potato production and utilization in the world. Potato Res., 19:37-72.

Vijayan, M. R. and Aiyers, R. S. 1969. Effect of N and P on the yield and quality of cassava. Agri. Res. J. Kerala, 7(2):84-90.

Vries, C. A. de, Ferwerda, D. D. and Flach, M. 1967. Choice of food crops in relation to actual and potential production in the tropics. Neth. J. Agric. Sci., 15:241-248.

Wijk, W. R. van 1966. Introduction, the physical method. pp. 1-16. In (W. R. van Wijk, ed.) Physics of plant environments. Wiley, New York.

Yong, C. W. 1970. Varieties and NPK fertilizers for tapioca (Manihot utilissima Pohl) on peat. Malaysian Agric. J., 47(4):483-491.

Yost, R. S. and Fox, F. L. 1979. Contribution of mycorrhiza to the P nutrition of crops growing on an Oxisol. Agron. J. (submitted).